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COMPUTER SIMULATION OF AN AIRCRAFT ENGINE FUEL INJECTION SYSTEM--ETC(U)
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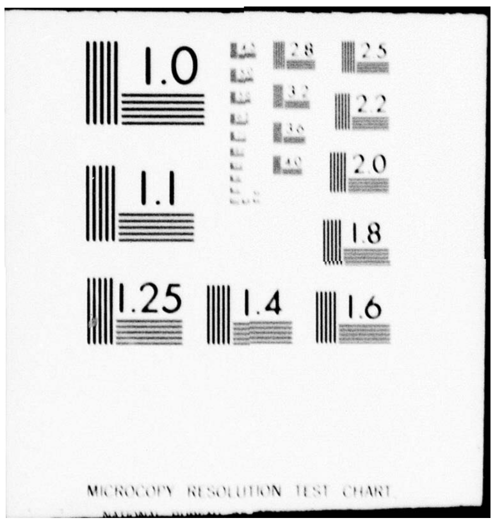
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# COMPUTER SIMULATION OF AN AIRCRAFT ENGINE FUEL INJECTION SYSTEM.

10 David D. Hester

9 FINAL REPORT,

15 DOT-FA74NA-1091

11 SEP[redacted]78

12 93 p.

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This investigation, performed under a contract administered by the Nat'l Aviation Facilities Experimental Center, Atlantic City, N.J., fulfills the requirements of NAFEC Contract DOT FA74NA-1091, Phase III.


16. Abstract

The purpose of phase III of the contract was to develop an analytical model of the Teledyne Continental fuel system to provide a basis for quantitatively exploring deficiencies in the system response which lead to poor exhaust emission characteristics. A computer model of the fuel system was developed based on component testing and found to give accurate predictions for pressures and flow rates within the system. The model has been used to investigate modifications to the system for improved fuel management and reduced exhaust emissions. The effect of improved fuel management on engine exhaust emissions was evaluated.


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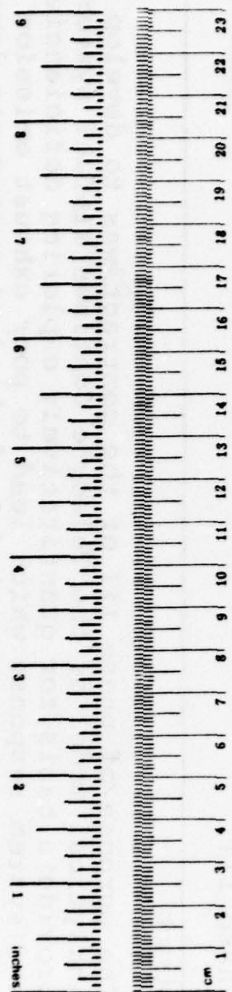
# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

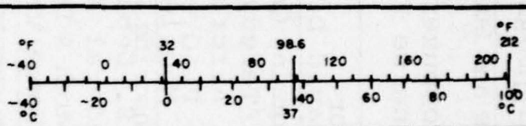
| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.




## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



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## LIST OF ILLUSTRATIONS

List of Illustrations - Cont'd.

## LIST OF SYMBOLS

| Symbol | Meaning | Units |
|---|---|---|
| $A$ | Area | Square Inch |
| $A_e$ | Relief Valve Diaphragm Effective Area | Square Inch |
| $A_v$ | Valve Area | Square Inch |
| CHT | Cylinder Head Temperature | Degrees Fahrenheit |
| $C_d$ | Orifice Discharge Coefficient | - |
| D | Line Diameter | Inch |
| DISP | Pump Displacement | Cubic Inch |
| EGT | Exhaust Gas Temperature | Degrees Fahrenheit |
| F | Objective Function | - |
| F1-F11 | Remainder Terms from Flow Equations | - |
| F ($\Delta$P) | Pump Leakage function | Pounds per Hour |
| F/A | Fuel to Air Mass Ratio | - |
| $K_f$ | Line Loss Factor | - |
| $K_o$ | Line Loss Factor for Bends, Valves and Fittings | - |
| $K_s$ | Spring Constant | Pounds per Inch |
| L | Line Length | Inch |
| N | Pump Speed | Revolutions per Minute |
| PAMB | Ambient Pressure | Pounds per Square Inch Absolute |
| P1 | Pump Inlet Pressure | Pounds per Square Inch Absolute |
| P2 | Pump Discharge Pressure | Pounds per Square Inch Absolute |

List of Symbols - cont'd

| Symbols | Meaning | Units |
|---|---|---|
| P3 | Ambient Pressure | Pounds per Square Inch Absolute |
| P4 | Nozzle Inlet Pressure | Pounds per Square Inch Absolute |
| P5 | Turbo Discharge Pressure | Pounds per Square Inch Absolute |
| P6 | Variable Orifice Discharge Pressure | Pounds per Square Inch |
| P7 | Vapor Return Line Pressure | Pounds per Square Inch |
| Pds | Downstream Pressure | |
| Q | Fluid Dynamic Head | |
| Re | Reynolds Number | - |
| $R_r$ | Orifice Rod Radius | Inch |
| $R_o$ | Variable Orifice Radius | Inch |
| RF | Fuel Pressure Force on Variable Orifice Rod | |
| RPM | Pump or Engine Rotational Speed | Revolutions per Minute |
| T | Temperature | Degrees Fa |
| W | Mass Flow Rate | Pounds per Hour |
| ZO | Supply Line Elevation at Tank | Inch |
| Z1 | Supply Line Elevation at Pump | Inch |
| $\Delta LS$ | Relief Valve Spring Compression | Inch |
| $\Delta P$ | Pressure Differential | Pounds per Square Inch |
| $\Delta P_v$ | Valve Pressure Differential | Pounds per Square Inch |

List of Symbols - cont'd

| Symbols | Meaning | Units |
|---|---|---|
| $\Delta P_t$ | Throttle Pressure Drop | Pounds per Square Inch |
| $\delta$ | Variable Orifice Displacement from Closed Position | Inch |
| $\delta_{ADJ}$ | Variable Orifice Adjustment | Inch |
| $\varepsilon$ | Surface Roughness | Inch |
| $\eta$ | Pump Efficiency | - |
| $\mu$ | Fluid Viscosity | Pounds Mass per Foot Per Second |
| $\rho$ | Fluid Density | Pounds Mass per Cubic Foot |

# INTRODUCTION

## Purpose

The purpose of this report is to develop a computer simulation of the TCM fuel injection system to serve as a tool for the evaluation of schemes for improved fuel management. Using the simulation, the effects of fuel system modifications on fuel flow rate are evaluated at various engine operating and environmental conditions. The impact of modifications on emissions and fuel economy are determined.

## Background

This report describes work performed under the first option of Phase III of National Aviation Facilities Experimental Center (NAFEC) contract DOT FA74NA-1091 by Teledyne Continental Motors (TCM). Prior testing of TCM engines under Phase I of this contract has shown that a significant reduction in emissions is available through improved fuel management. Phase II of the contract entitled "Corrective Measures Determination" involves an investigation of concepts which offer the most promise toward achieving the emissions levels required by proposed Environmental Protection Agency (EPA) standards. However, analysis accomplished under a National Aeronautics and Space Administration (NASA) contract (NASA contract NAS3-19755) fulfilled the purpose of Phase II, eliminating the need for duplicating this effort under NAFEC contract (reference 1). Phase III of the NAFEC contract DOT FA74NA-1091 was concerned with the analysis, design, construction and testing of fuel injection system based on the system currently manufactured at Continental.

Phase III was divided into three options. The objectives of the first option were:

(1) Define the fuel system requirements.
(2) Develop a generalized analytical model of the TCM fuel injection system.
(3) Measure the response of the TCM fuel injection system to varied operational conditions.
(4) Refine the analytical model to correlate with system measurements.
(5) Use the model to predict component requirements for fuel/air ratio control.

This report describes the work performed under the first option of Phase III. The second and third options were concerned with the modification of the current system and subsequent testing. These options were cancelled due to a proposed elimination of the emissions standards for aircraft piston engines.

## Overview

To understand the Continental fuel injection system and its effects on aircraft engine emissions, it is necessary to understand the operating limitations of the air-cooled aircraft internal combustion engine. These limitations are primarily imposed by cooling requirements, detonation limits, and acceleration characteristics of the engine. The Continental fuel injection system was designed to avoid over-heating and detonation by supplying excess fuel at high power. A typical fuel flow schedule is shown in figure 1, which shows an increase in the slope of the fuel flow schedule above 75 percent power to provide additional fuel for cooling. At cruise power (75 percent) and below, the primary consideration is engine acceleration, although cooling can be a problem during aircraft ground operations (taxi).

In order to obtain better cruise economy for steady state operation, the Continental system is equipped with a manual mixture control. This control is a fuel pump bypass which is used at the option of the pilot at 75 percent power and below to reduce fuel flow. Figure 2 shows the benefits of leaning. Although power drops with increasingly lean fuel/air ratios, specific fuel consumption drops approximately 15 percent from best power fuel/air to best economy fuel/air. Below 75 percent power, manual leaning is limited by instructing the pilot to lean no more than 50° Fahrenheit (F) rich of peak exhaust gas temperature (EGT). Figure 1 shows the region of the fuel schedule where manual leaning is permitted.

The effect of leaning on engine emissions was investigated during phase I of (NAFEC) contract DOT FA74N1091 (reference 2) where it was found that leaning generally reduces hydrocarbons (HC) and carbon monoxide (CO) while increasing nitrogen oxides (NO). For the baseline engines, HC and CO emissions exceed (EPA) standards. However, NO emissions are considerably below the standards. Therefore, leaning is a means of reducing the emissions which exceed the EPA standards. Improvement must be

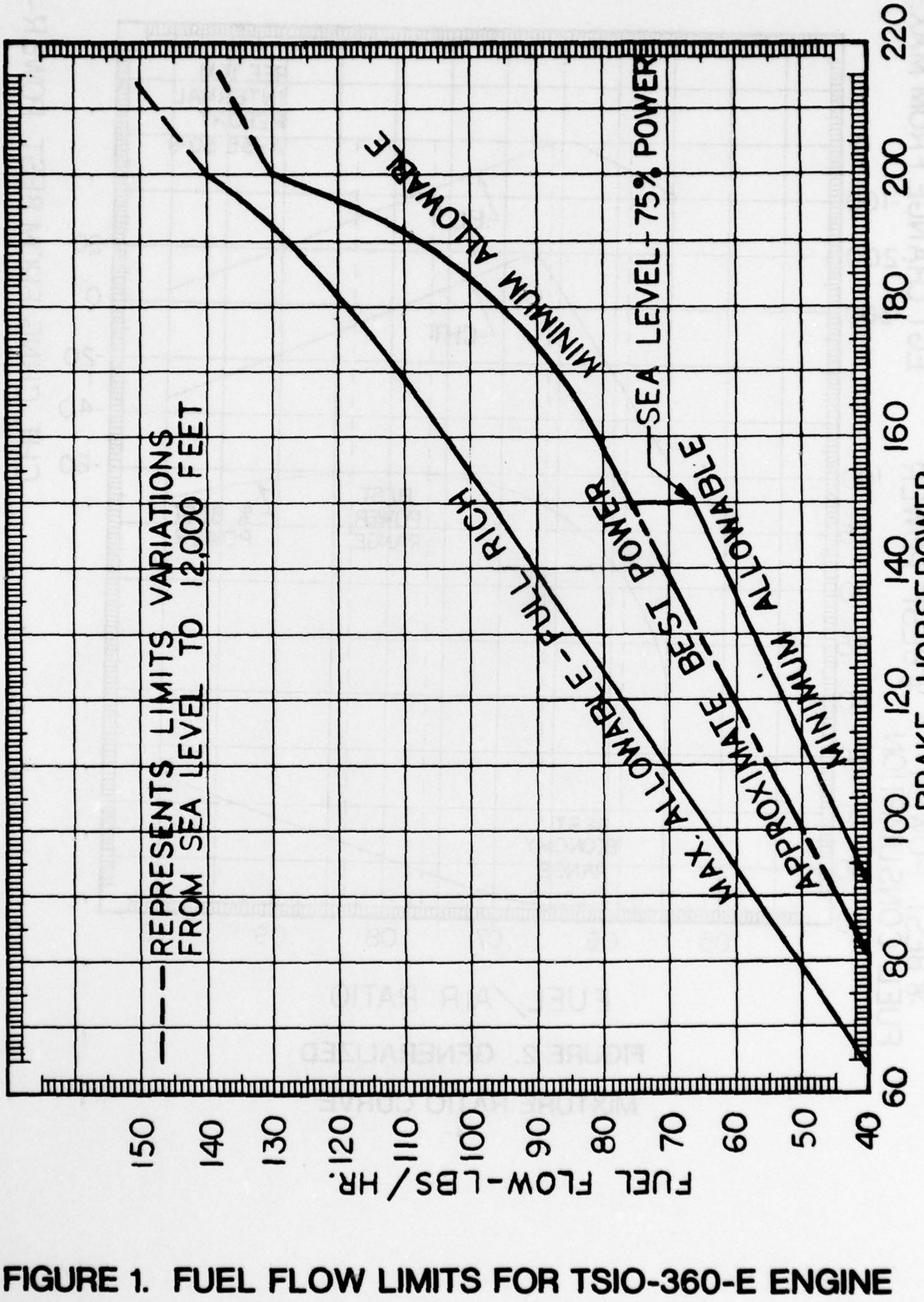


FIGURE 1. FUEL FLOW LIMITS FOR TSIO-360-E ENGINE

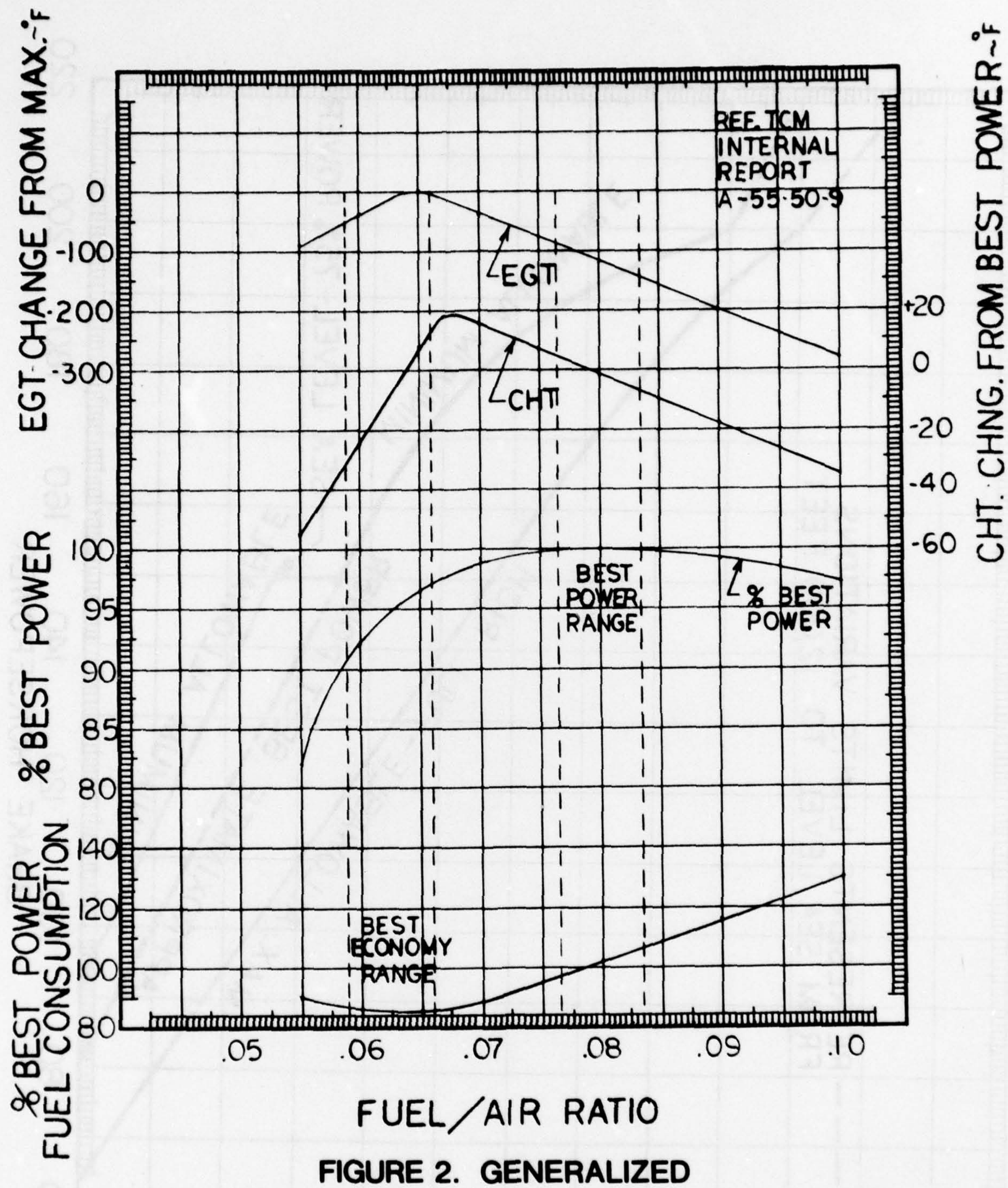


**FIGURE 2. GENERALIZED MIXTURE RATIO CURVE**

made to the current fuel injection system and perhaps the air intake manifold to safely lean for reduced emissions during the landing and takeoff (LTO) cycle, where the engines are operated full rich.

Improvements to the fuel system in the form of additional or modified hardware cannot be made without an understanding of the fluid behavior within the system. Phase III, Option I, of the NAFEC Contract DOT-FA74NA1091 was awarded to Teledyne Continental Motors (TCM) to investigate the current fuel injection system and develop an analytical simulation. This simulation is to serve as the basis for quantitatively exploring deficiencies in the fuel system which lead to poor exhaust emissions characteristics. The simulation was based on component behavior as determined from component bench tests. The model was written in modular format to readily allow simulation of fuel system hardware changes for improved fuel management.

## DISCUSSION

### Description of the Continental Fuel Injection System

The fuel injection system chosen for simulation is designed for the TSIO-360-E and LTSIO-360-E engines. These engines currently lead Continental's line of turbocharged engines for rate of production. The LTSIO-360-E and TSIO-360-E are counter-rotating 200 horsepower engines produced for the rapidly expanding twin engine aircraft market. The fuel system used on these engines was developed by modifying previous Continental designs and shares many common components with other Continental fuel systems. The components of the system are shown in figure 3. Injector nozzles spray fuel continuously into the intake port of each cylinder where the fuel is further vaporized by cylinder air intake. The fuel/air mixture enters the combustion chamber when the intake valve opens. The amount of fuel delivered is determined by engine speed, turbocharger discharge pressure, throttle angle, and ground trim adjustments.

A schematic of the fuel injection system used on Continental turbocharged engines is shown in figure 4. The heart of the system is a rotary vane pump which is driven at a 1:1 ratio by the engine and delivers flow in direct proportion to engine speed. The pump is bypassed by the variable orifice and idle relief valve which to a large extent govern the output pressure of the pump. As more flow is bypassed at a constant pump speed, pump pressure drops. The idle relief valve is effective at low pump speeds and is ground adjusted to set the minimum pump discharge pressure at idle. The variable orifice is ground-adjusted to trim pump pressure at full power. The action of the aneroid adjusts the variable orifice rod to increase pump discharge pressure with increasing turbocharger discharge pressure. This aneroid action tends to increase fuel flow as air density increases with turbocharger pressure, tending to hold a constant fuel/air ratio. However, no compensation for ambient air temperature effects on air density are made, as the aneroid is insensitive to temperature.

From the pump, fuel flow to the engine is metered by an orifice which is directly linked to the air throttle. The size of the orifice is a function of the throttle position. Orifice size tends to increase as the throttle is opened, increasing fuel flow as manifold pressure and engine airflow increase. Fuel pressure downstream of the throttle valve (metered fuel pressure) is fed to the manifold valve and nozzle. The rate of fuel flow entering the cylinders depends on the fluid pressure

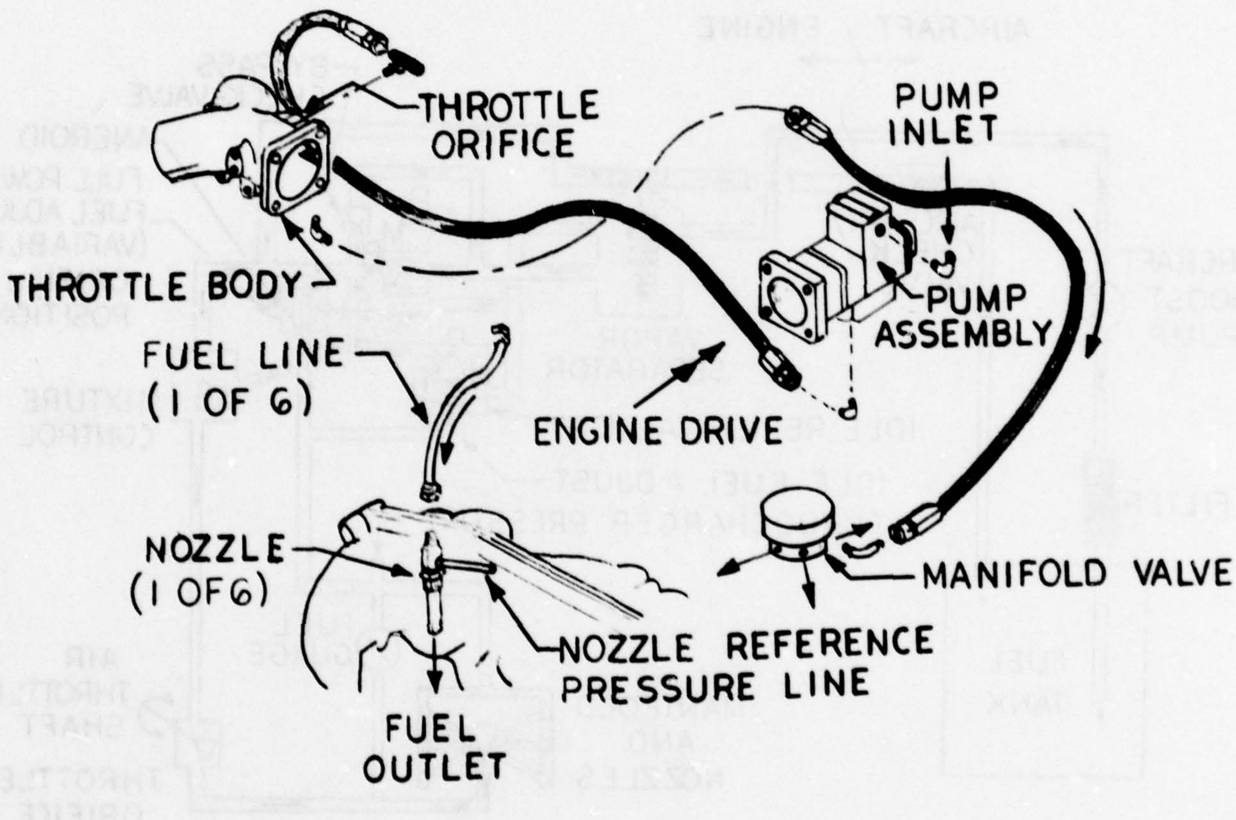


**FIGURE 3. FUEL INJECTION SYSTEM HARDWARE**

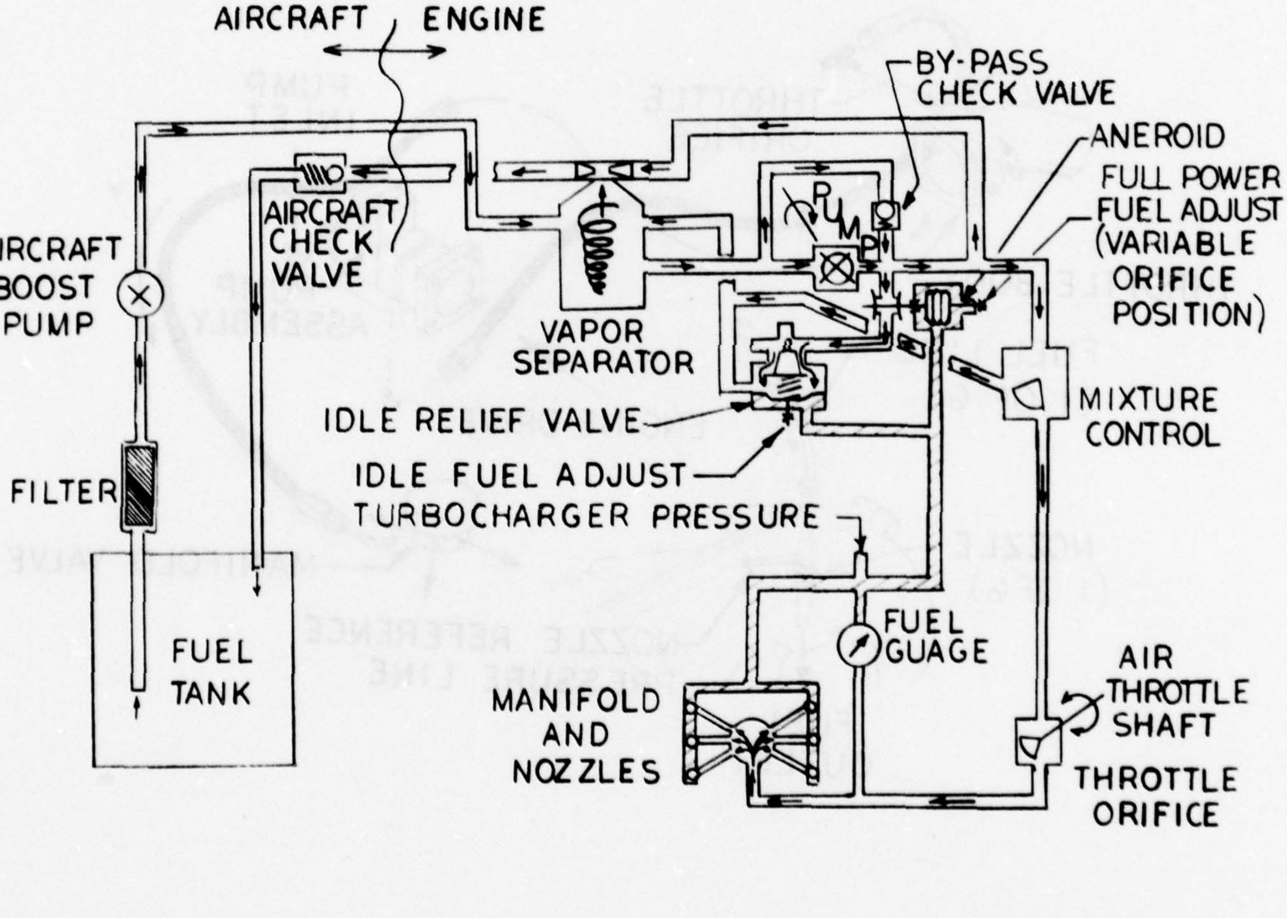


**FIGURE 4. FUEL INJECTION SYSTEM SCHEMATIC**

of the fuel relative to the reference pressure of the nozzles. For turbocharged engines, turbocharger discharge pressure is used as a nozzle reference pressure. The manifold valve, nozzle lines, and nozzles are factory calibrated as a unit so that fuel flow rate is a set function of metered fuel pressure (figure 5). The function of the manifold valve is to distribute fuel flow to the individual fuel nozzles and to abruptly chop the fuel flow when metered fuel pressure drops below the idle cutoff level.

Fuel/air mixture ratio is manually leaned by the pilot by opening a fuel pump bypass valve which reduces fuel pump discharge pressure. Since this action reduces fuel flow without affecting airflow, the fuel/air ratio is reduced.

## Description of the Fuel System Model

Simulation of the fuel injection system involves the solution of a fluid flow network to determine the flow rate and pressures within the system. The approach used to simulate the fuel system is described in detail in reference 3. Using this approach, the flow versus pressure drop relationship for each component of the system was first established using an equation or curve fit based on component flow testing. Next, a set of governing equations was established using two basic hydraulic principles:

Flow continuity (1)

$$\Sigma(\text{flows entering a junction}) = 0$$

Continuity of Potential (2)

$$\Sigma(\text{pressure changes across a closed flow path}) = 0$$

These equations form a set of nonlinear simultaneous equations which can be solved with the help of a computer iterative technique. The technique employed, Rosenbrock's algorithm, uses initial guesses for the unknowns and improves the guesses using the set of simultaneous equations. Successive iteration leads to a set of pressures and flow rates which satisfy equations 1 and 2. The accuracy of the initial guesses is not critical and satisfactory solutions can be obtained within about 5,000 iterations.

The fuel system model employed is shown in figure 6. There are 11 unknowns for the system, six pressures and five flow rates:

P1 - Pump inlet Pressure, X(1)
P2 - Pump discharge pressure, X(2)
P3 - Fuel metered pressure, X(3)
P4 - Nozzle inlet pressure, X(4)
P6 - Variable orifice discharge pressure, X(5)
P7 - Vapor return line pressure, X(6)
WA - Supply line flow rate, X(7)
WB - Pump flow rate, X(8)
WC - Vapor separator flow rate, X(9)
WD - Variable orifice flow rate, X(10)
WE - Fuel system output flow rate, X(11)

Of course, one of the unknowns is the desired fuel output of the system, WE. In order to solve for the 11 unknowns, there must be a set of 11 simultaneous equations. These are composed of two flow continuity equations and nine continuity of potential equations:

Flow continuity at junction 0

WA-WE-WC=0 (3)

Flow continuity at junction 1

WB-WA-WD=0 (4)

$PAMB-P1-(DP)_{SL} = 0$ (5)

Where $(DP)_{SL}$ = Supply Line Pressure drop

PAMB = Ambient pressure (known)

P2-P1- Pump Pressure Rise = 0 (6)

P2-P6- Variable Orifice Pressure Drop = 0 (7)

P6-P1- Idle Relief Valve Pressure Drop = 0 (8)

P2-P7- Vapor Separator Pressure Drop = 0 (9)

P2-P3- Control Unit Pressure Drop = 0 (10)

P3-P4- Mainfold Valve Pressure Drop = 0 (11)

P4-P5- Nozzle Pressure Drop = 0 (12)
Where P5 = Turbocharger discharge pressure (known)

P7-PO- Return Line Pressure Drop = 0 (13)
Where PO = Ambient pressure (known)

These 11 equations were formed into 11 separate computer subroutines. Each subroutine is used to calculate the value of one of the sums based on assumed values for the 11 unknowns and known boundary values. The correct assumptions for the unknowns will yield 11 sums which each equal zero. To find a solution to the problem using Rosenbrock's algorithm, an objective function is formed using the remainder terms from each of the 11 functions:

$$F = F1^2 + F3^2 + \ldots + F11^2$$

Where F1 = WA-WE-WC

F2 = WB-Wa-WD

F3 = PO-P1 - Supply line pressure drop

.

.

.

F11 = P7-PO- Return line pressure drop

After calculating the objective function (F) based on assumptions for the 11 variables, new values for the unknowns are formed within the algorithm. A new value of the objective function is calculated using the 11 subroutines. If the magnitude of the objective function is less than the previous value, the new values for the unknowns are accepted. Successive iterations are continued until the objective function is reduced to a small positive value. The magnitude of the objective function is a measure of the error of the solution, and can be used as a criteria for convergence. For this study, the maximum value of the objective function was set at 0.001 which gave flow rates correct to within approximately 0.10 pounds per hour.

The use of subroutines within the computer code gives the simulation the flexibility needed to allow evaluation of modifications to the fuel system. Changes which would require extensive bench and flight testing of the entire fuel system

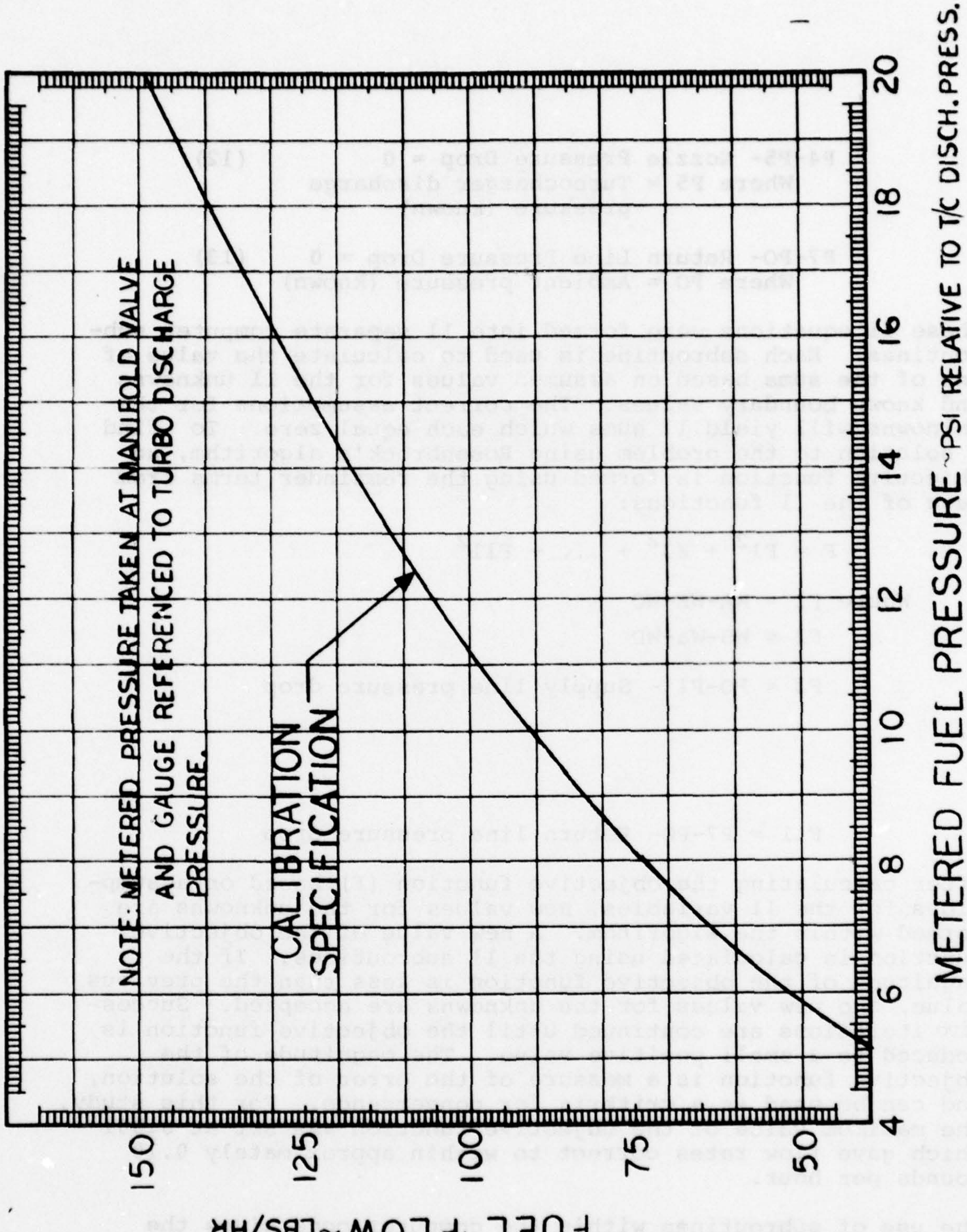


**FIGURE 5. METERED FUEL ASSEMBLY CALIBRATION**

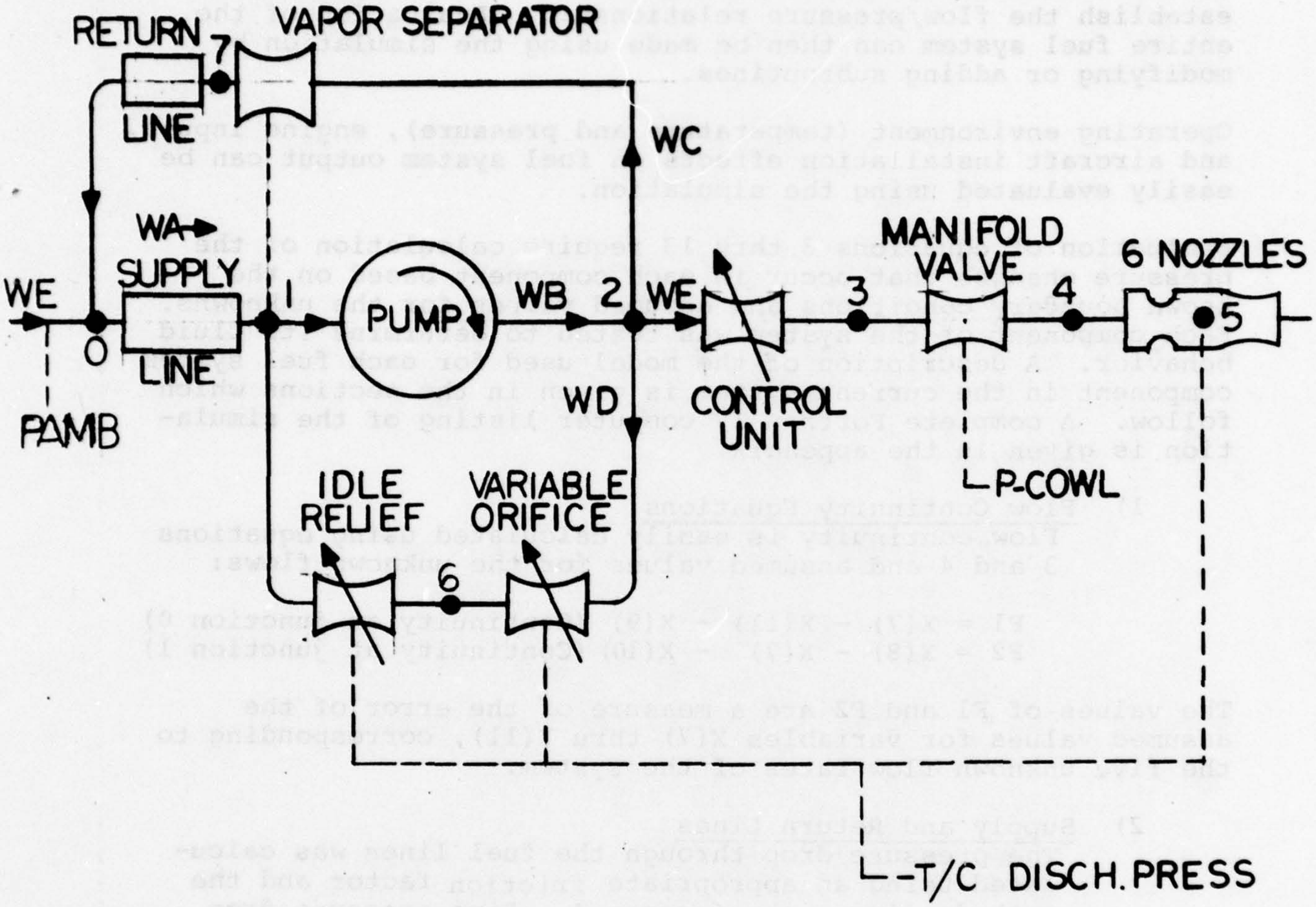


**FIGURE 6. FUEL SYSTEM MODEL**

can be evaluated by bench testing only the new component to establish the flow/pressure relationship. Evaluation of the entire fuel system can then be made using the simulation by modifying or adding subroutines.

Operating environment (temperature and pressure), engine inputs, and aircraft installation effects on fuel system output can be easily evaluated using the simulation.

Evaluation of equations 3 thru 13 require calculation of the pressure changes that occur in each component based on the known boundary conditions and assumed values for the unknowns. Each component of the system was tested to determine its fluid behavior. A description of the model used for each fuel system component in the current system is given in the sections which follow. A complete Fortran IV computer listing of the simulation is given in the appendix.

1) Flow Continuity Equations

Flow continuity is easily calculated using equations 3 and 4 and assumed values for the unknown flows:

F1 = X(7) - X(11) - X(9) (Continuity at junction 0)
F2 = X(8) - X(7) - X(10) (Continuity at junction 1)

The values of F1 and F2 are a measure of the error of the assumed values for variables X(7) thru X(11), corresponding to the five unknown flow rates of the system.

2) Supply and Return Lines

The pressure drop through the fuel lines was calculated using an appropriate friction factor and the methods given in reference 4. Line pressure drop is calculated as:

$$\Delta P = K_f * Q + \frac{\rho * (Z1-Z0)}{1728.}$$

Where $K_f = FF * L/D + K_o$

FF = 64./Re for laminar flow (Re < 3000)

FF = Value from Moody diagram (figure 7) for turbulent flow

L = Line length (inches)

D = Line diameter (inches)

$K_o$ = Dimensionless experimental coefficient accounting for head loss in bends, valves, fittings, etc. Available in numerous handbooks, (reference 4)

Re = Reynolds number

$$Re = \frac{W \times D}{\mu X A} \times \frac{12.}{3600.}$$

$\mu$ = Fluid viscosity, $Lb_m$ / ft-sec

$\rho$ = Density of fluid ($lbm/ft^3$)

ZO = Elevation of line at fluid inlet (inches)

Z1 = Elevation of line at flow exit (inches)

Q = Fluid dynamic head (psi)

$$= 1/2 * \frac{W * |W| *144.}{(3600)^2 (\rho) (A^2) (32.2)}$$

W = Fluid flow rate (pph)

A = Cross-sectional area of line ($in^2$)

The friction factor (FF) for turbulent flow is a function of the line surface roughness relative to the line diameter and Reynolds number, as explained in reference 4. Surface roughness (EPSP) was estimated to be 125. microinches.

Fuel viscosity and density for low lead 100 Octane (LL100) aviation gasoline (Avgas) are built in functions of temperature as shown in figures 8 and 9 (reference 5).

For turbulent flow, friction factor is determined by interpolation of figure 7, which was built into the computer code. The friction factor for laminar flow is given by the equation:

$$FF = 64./Re \qquad \text{(reference 4)}$$

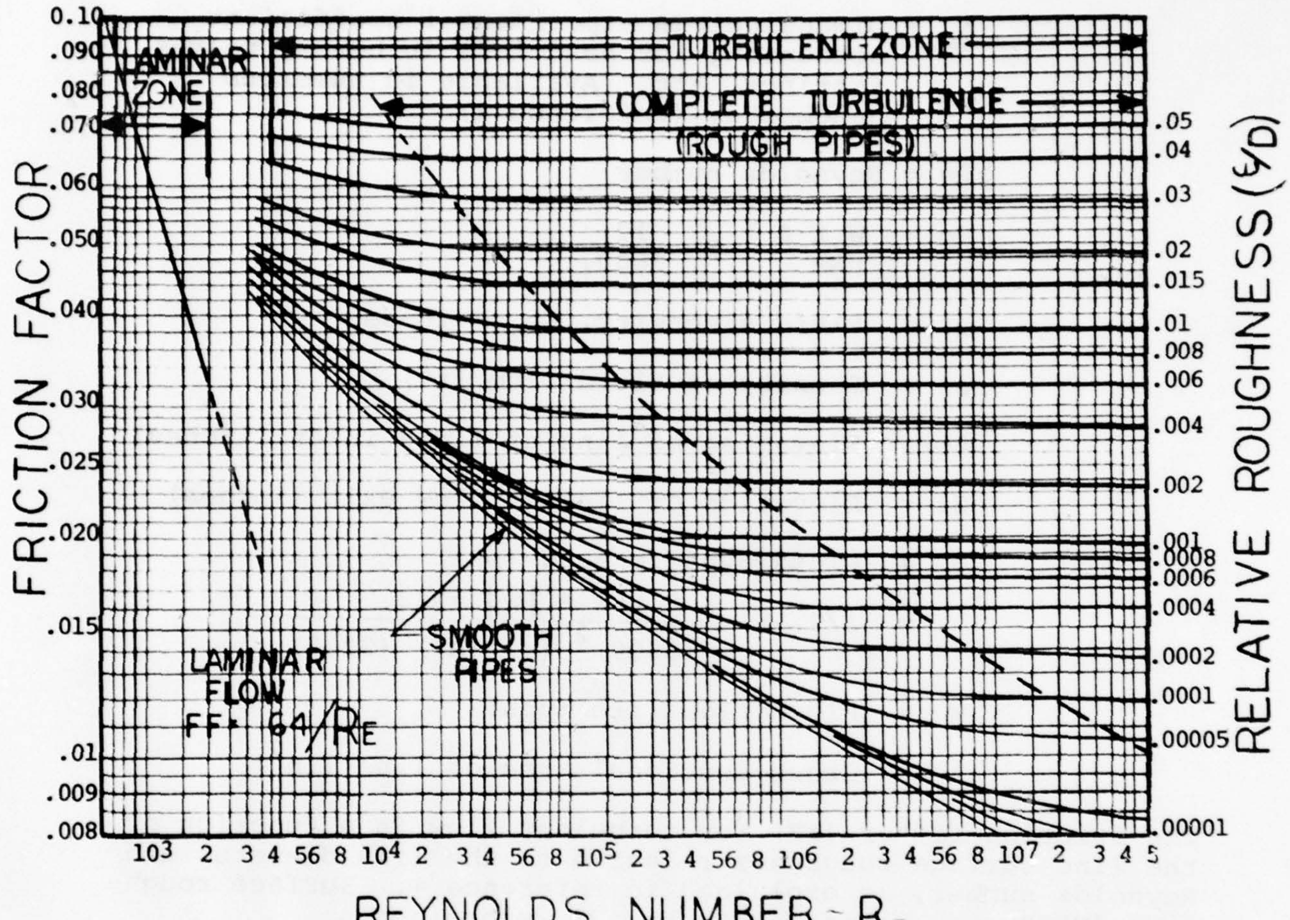


**FIGURE 7. FRICTION FACTORS FOR FULLY DEVELOPED FLOW**

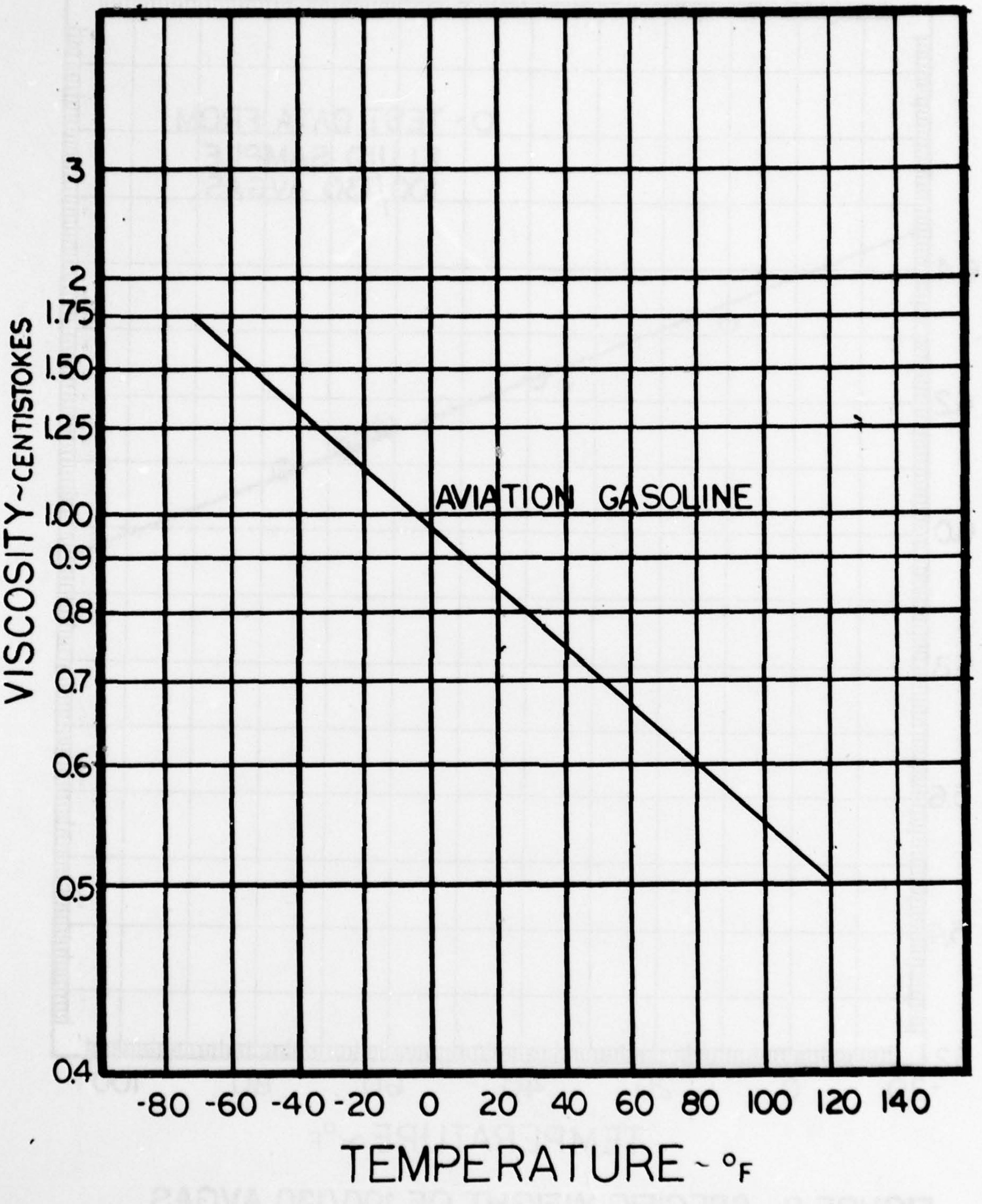


**FIGURE 8. VARIATION OF FUEL VISCOSITY WITH TEMPERATURE**

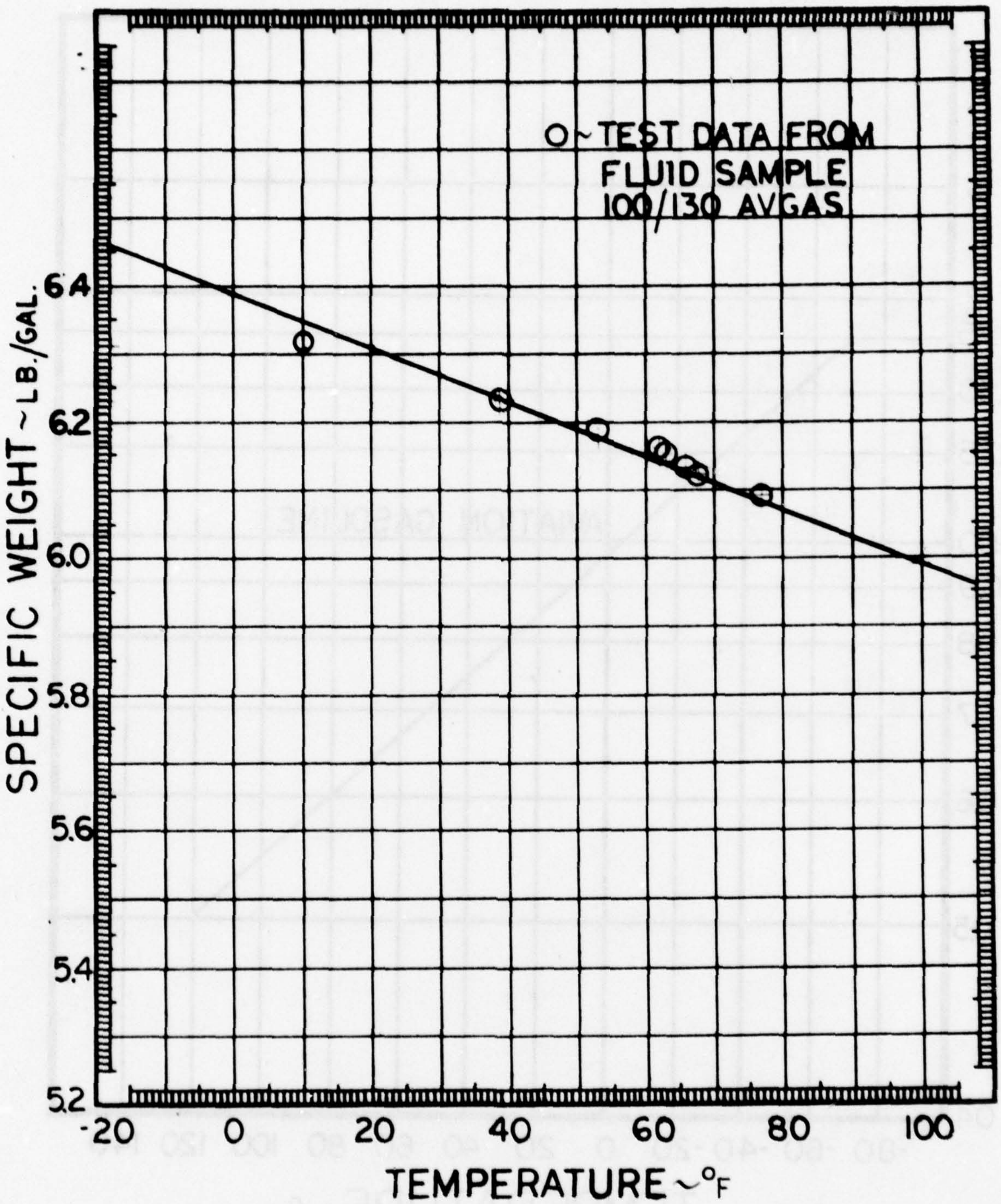


**FIGURE 9. SPECIFIC WEIGHT OF 100/130 AVGAS**

3) Fuel Pump

Bench tests were used to establish the fluid behavior of the rotary vane pump. Data from these tests is plotted in figures 10 and 11. Cross plots of the data show that pump output is proportional to pump speed for a given pump pressure rise (figure 12). An equation for the pump output was developed based on pump displacement and experimentally determined flow rate:

$$W = \left(\frac{\eta * \rho * DISP}{1728.}\right) * (60 * N) - F(\Delta P)$$

Where $\eta$ = pump efficiency (93.7 percent for the pump tested)

$\rho$ = fluid density

DISP = pump displacement ($in^3$)

N = pump speed (RPM)

$F(\Delta P)$ = pump leakage flow rate (PPH) (figure 13)

Pump leakage is due to internal pump flow used for bearing lubrication plus vane leakage. This flow is independent of pump speed and is a function of the pressure rise across the pump and vane tolerances as shown in figure 13.

4) Variable Orifice

A cross-sectional view of the variable orifice is shown in figure 14. Pressure loss through the variable orifice depends on the position of the orifice rod relative to the body of the orifice. Figure 15 shows the effect of varying flow rate and orifice position on orifice pressure loss as determined from bench tests. For constant orifice position, orifice pressure loss is proportional to the square of the flow rate. Orifice flow area varies as shown in figure 16, calculated from the known orifice and rod radii:

$$A = \pi \left[(Ro)^2 - (Rr)^2\right]$$

Where Ro = radius of unblocked orifice
Rr = radius of orifice rod

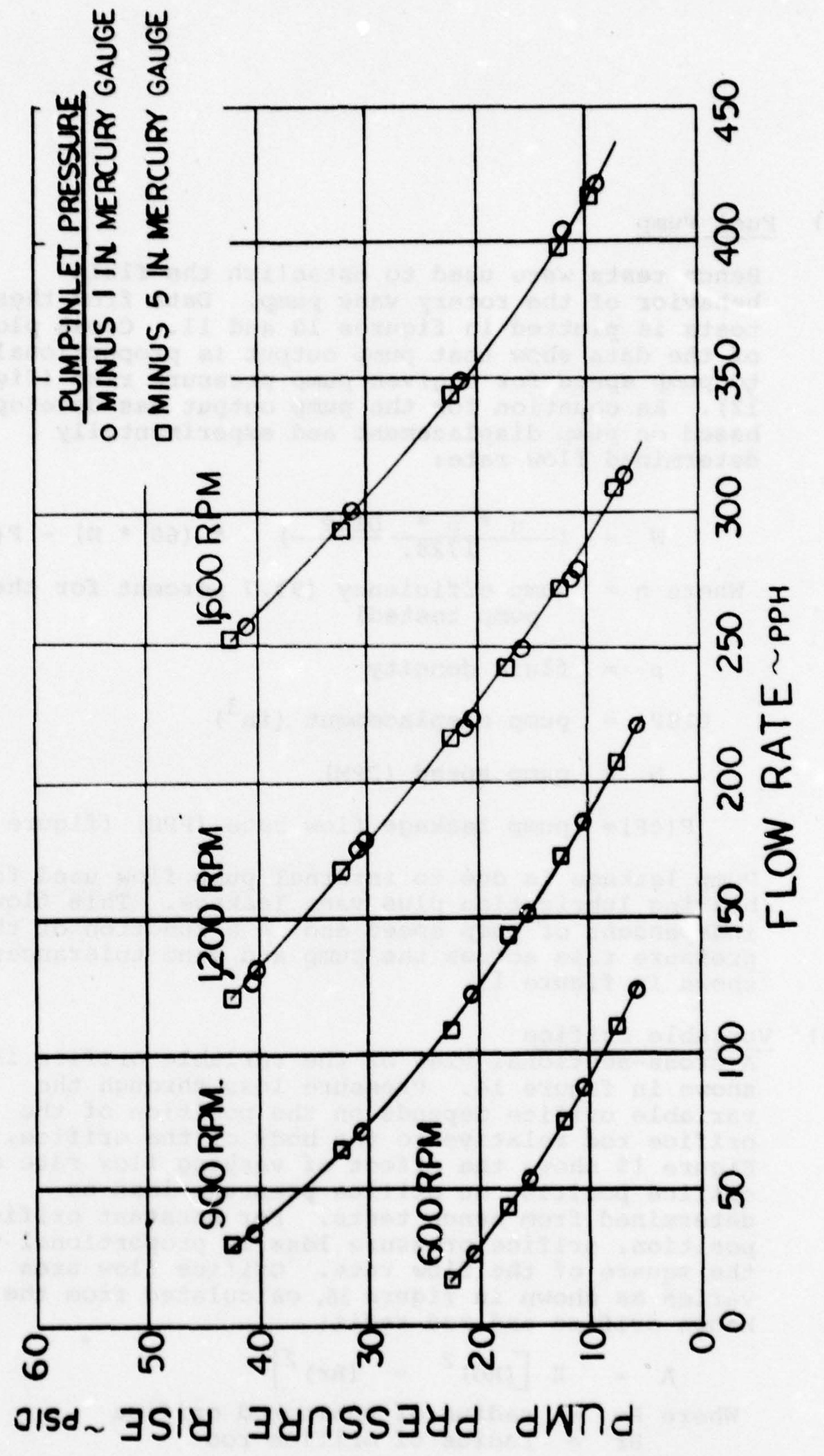


**FIGURE 10. VANE PUMP CALIBRATION**

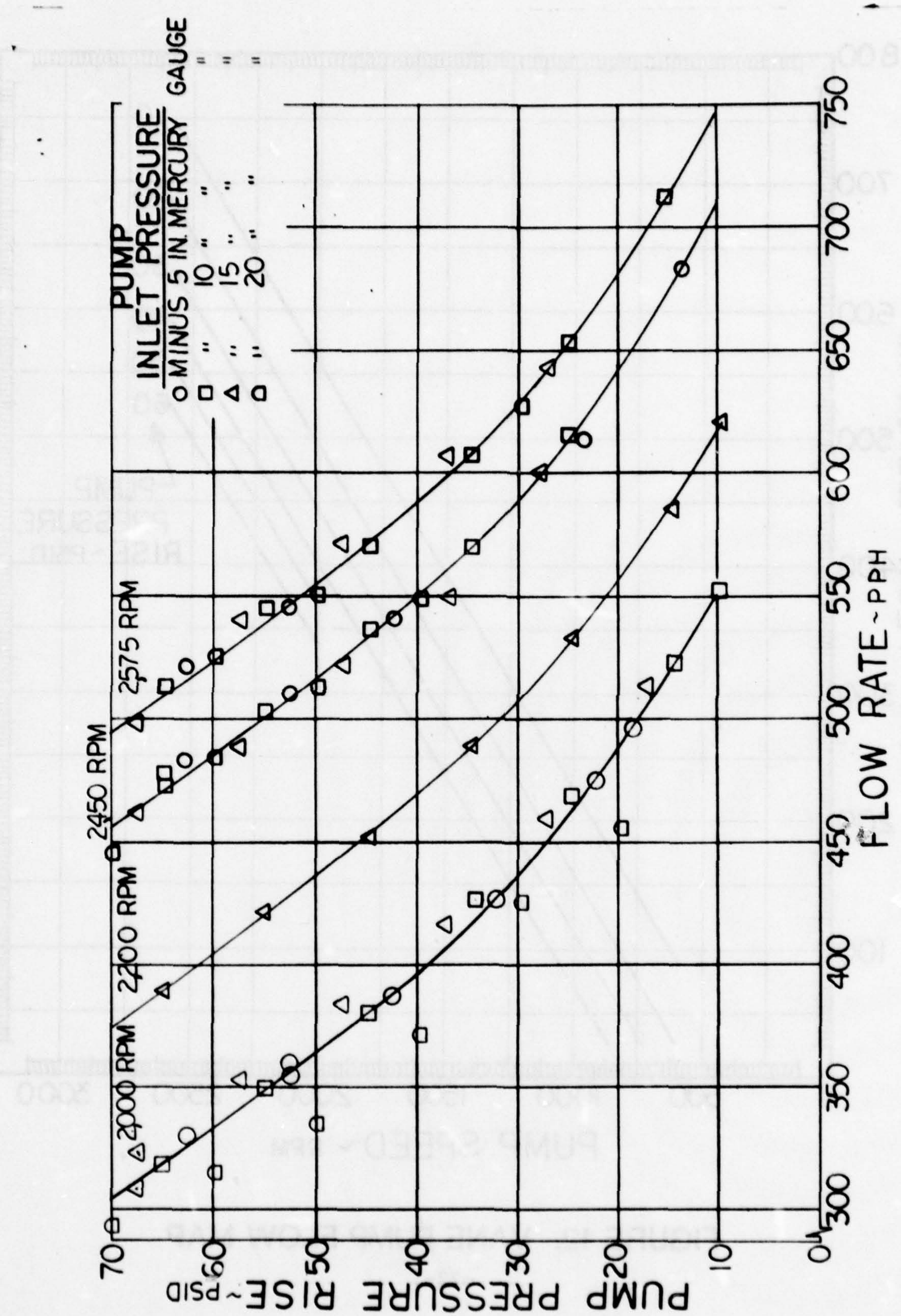


**FIGURE 11. VANE PUMP CALIBRATION**

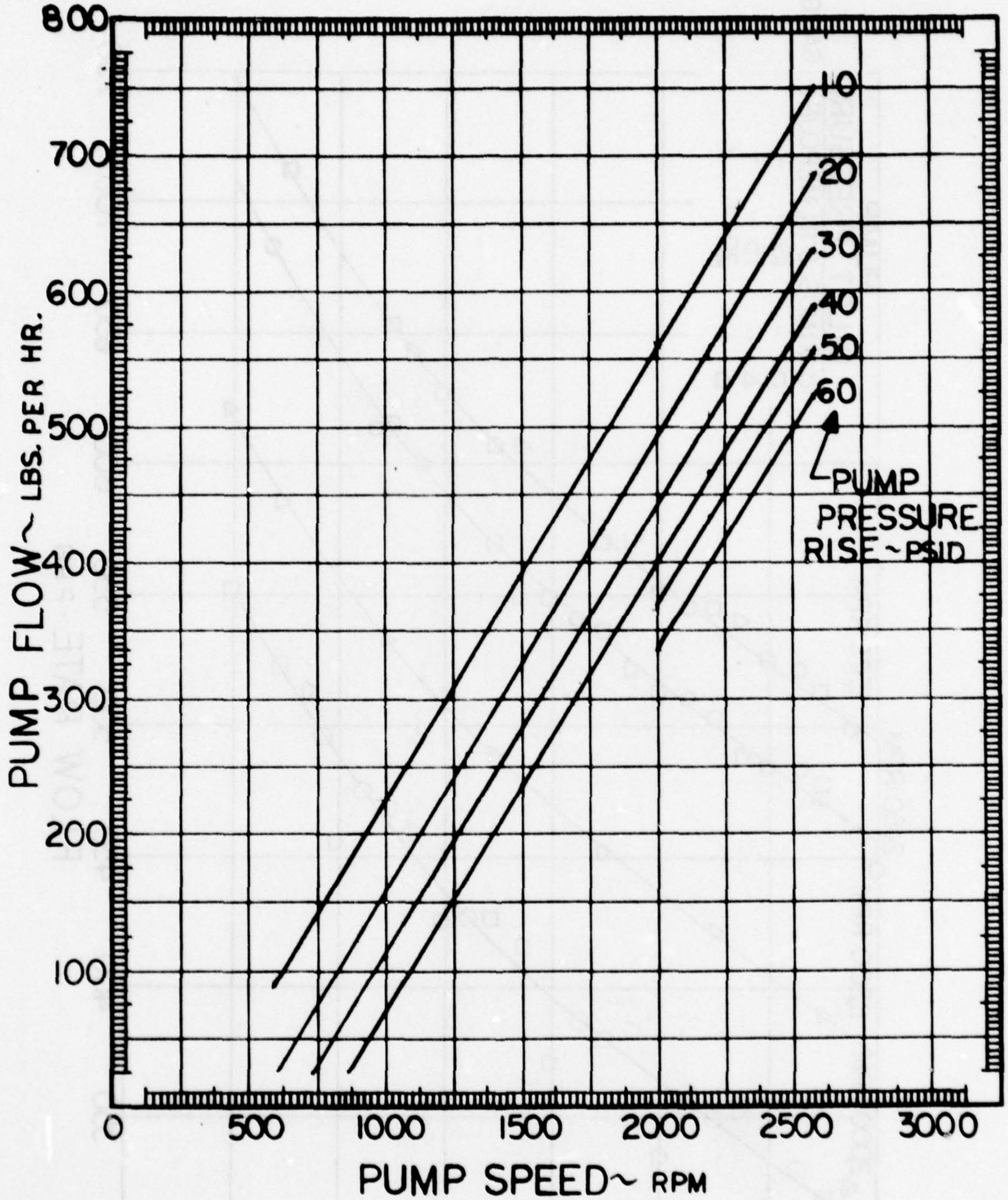


FIGURE 12. VANE PUMP FLOW MAP

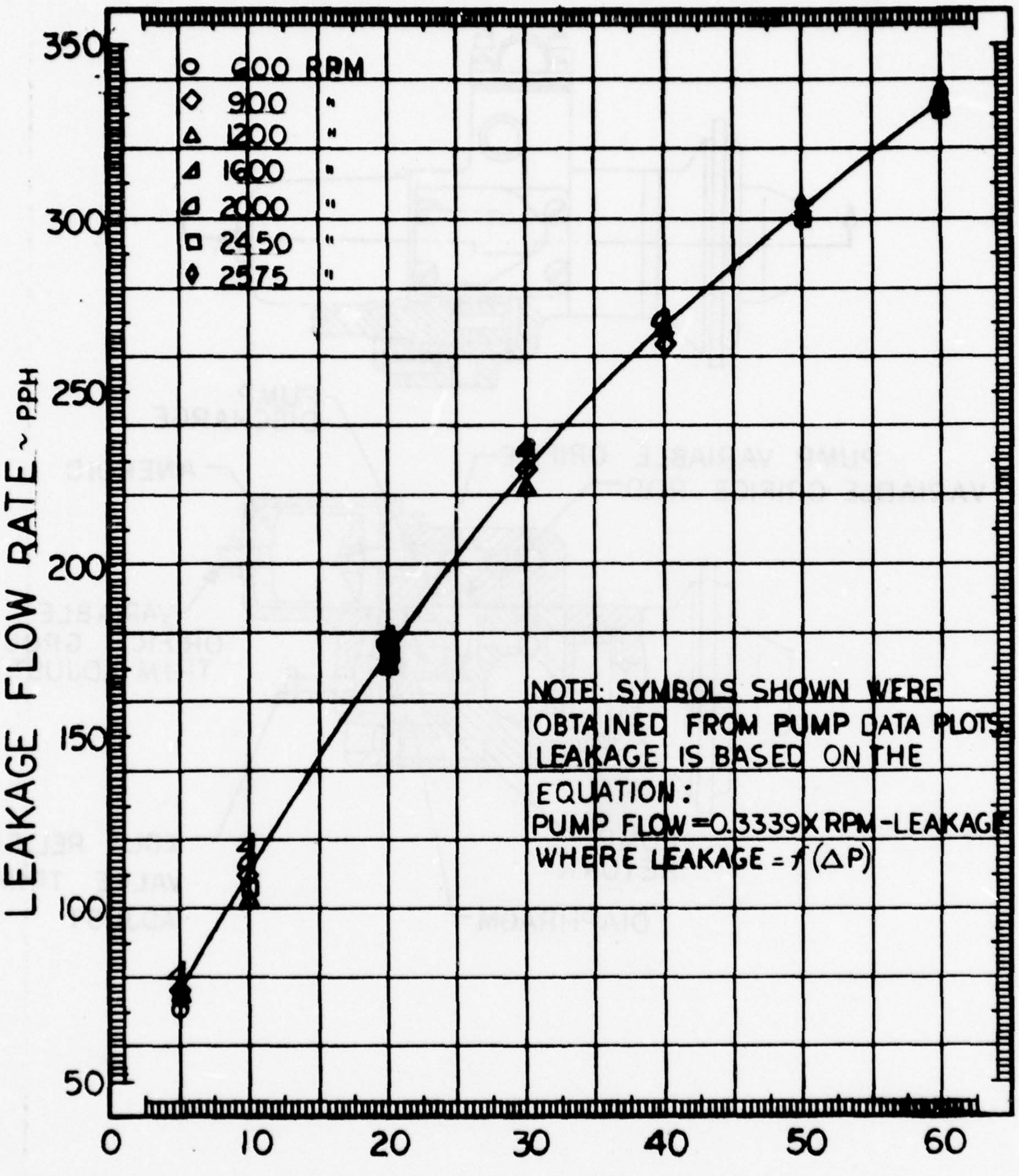


**FIGURE 13. VANE PUMP LEAKAGE**

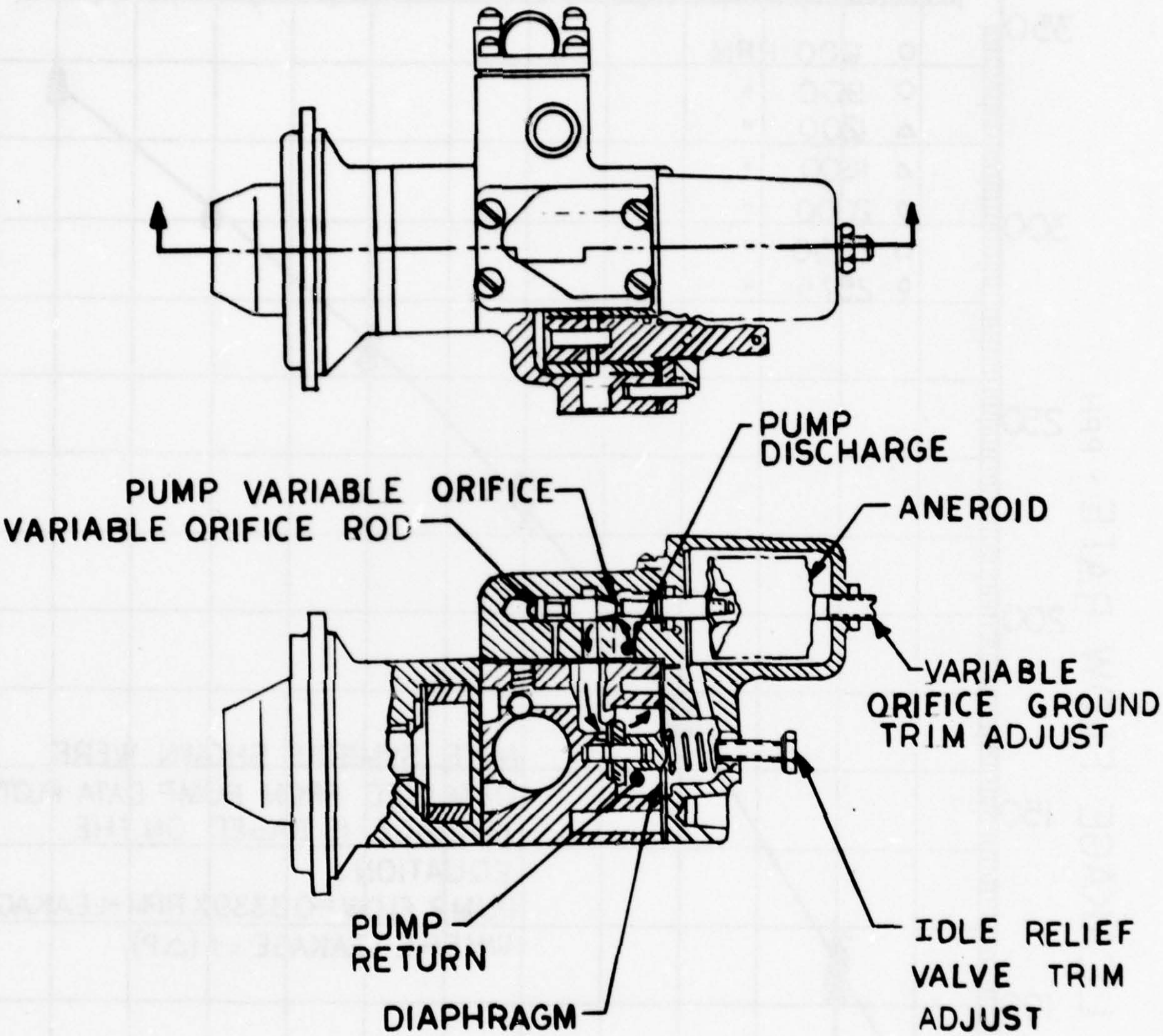


**FIGURE 14. FUEL PUMP ASSEMBLY**

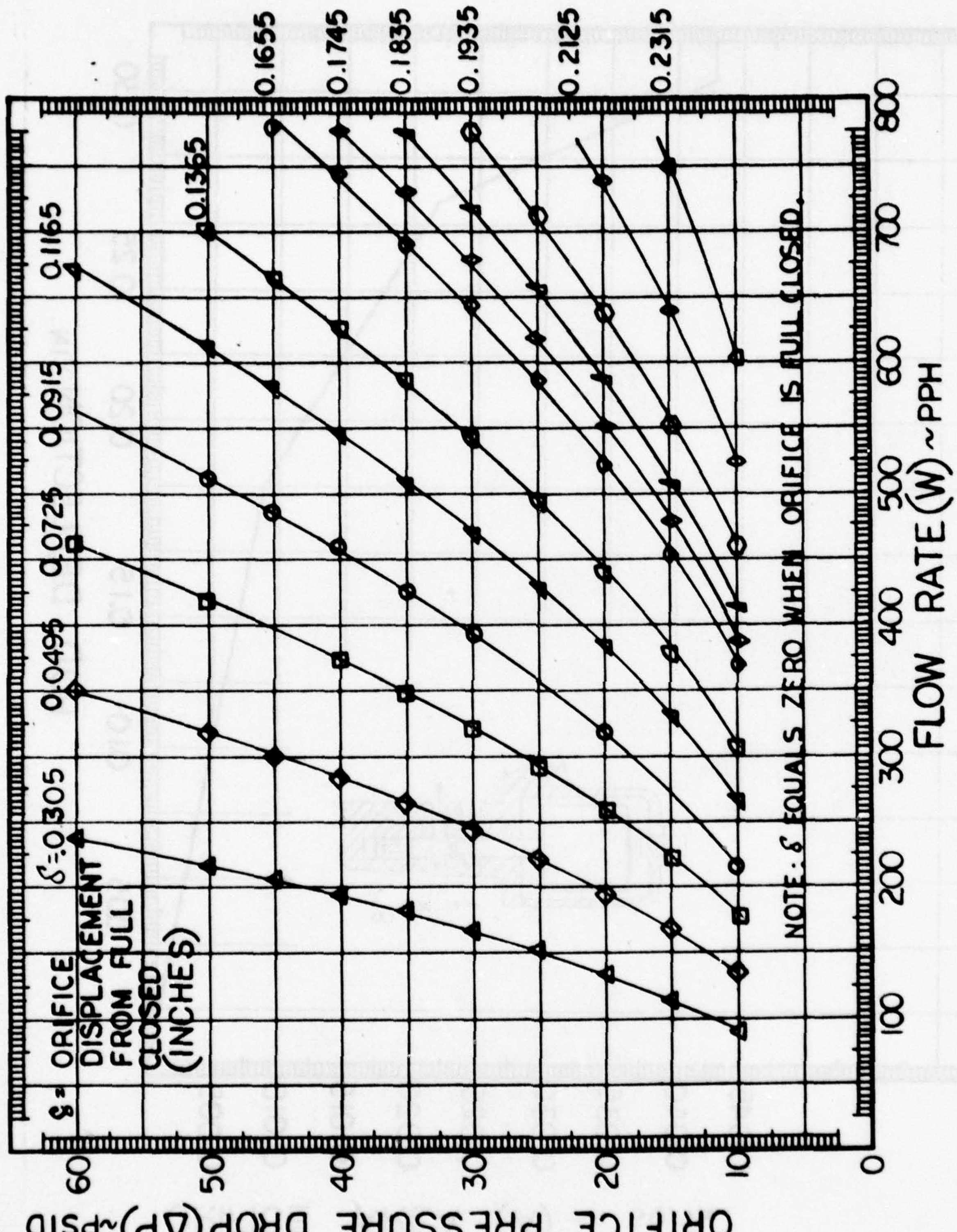


**FIGURE 15. VARIABLE ORIFICE CHARACTERISTICS**

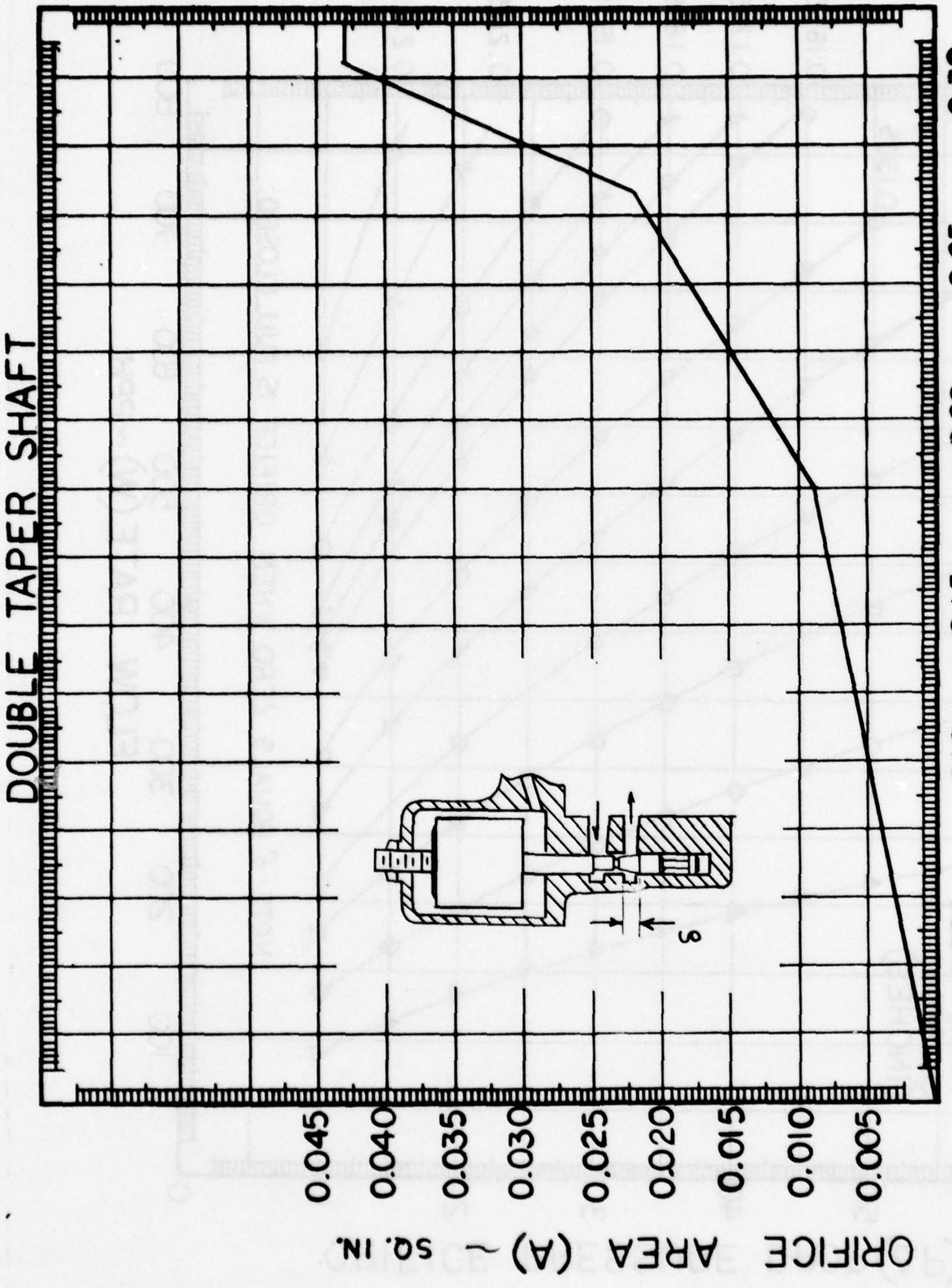


**FIGURE 16. VARIABLE ORIFICE FLOW AREA**

Based on the experimental data and analytical area calculations, an orifice dimensionless K-factor can be determined as a function of orifice area as shown in figure 17. Orifice pressure loss is then calculated using:

$$DP = K * Q$$

Where

$Q$ = Orifice dynamic head (psi)

$$= \frac{1/2}{(32.3)} \frac{\rho \quad * V^2}{(144.)}$$

and $V$ = mean flow velocity

$$V = \frac{W \quad * \quad 144.}{\rho * A * 3600.}$$

$W$ = Flow rate (pph)

$\rho$ = Density ($lbm/ft^3$)

$A$ = Orifice area ($in^2$)

This equation gives an orifice pressure drop proportional to the square of the orifice flow rate, in agreement with the data in figure 15.

In order to determine the orifice pressure loss, the position of the orifice must be known. The effect of reference pressure on aneroid movement is shown in figure 18. Tests indicate that changes in temperature do not produce significant aneroid movement. Changes in temperature from 80° F to 150° F cause aneroid movements on the order of 0.005 inches. Aneroid temperature insensitivity is ideal, since the temperature of the aneroid is not representative of induction air temperature.

Fuel pressure on the orifice rod produces movement of the rod, since the aneroid behaves as a linear spring (figure 19). Because of the interaction of fuel pressure forces on aneroid movement and vice versa, orifice pressure loss must be determined by iteration. The final orifice rod position is given by:

$$\delta = \delta \text{ adj.} + AMS\ (P_{adj} - P_5) - \frac{RF}{K} \qquad (14)$$

Where $\delta$ adj = Orifice rod adjusted position

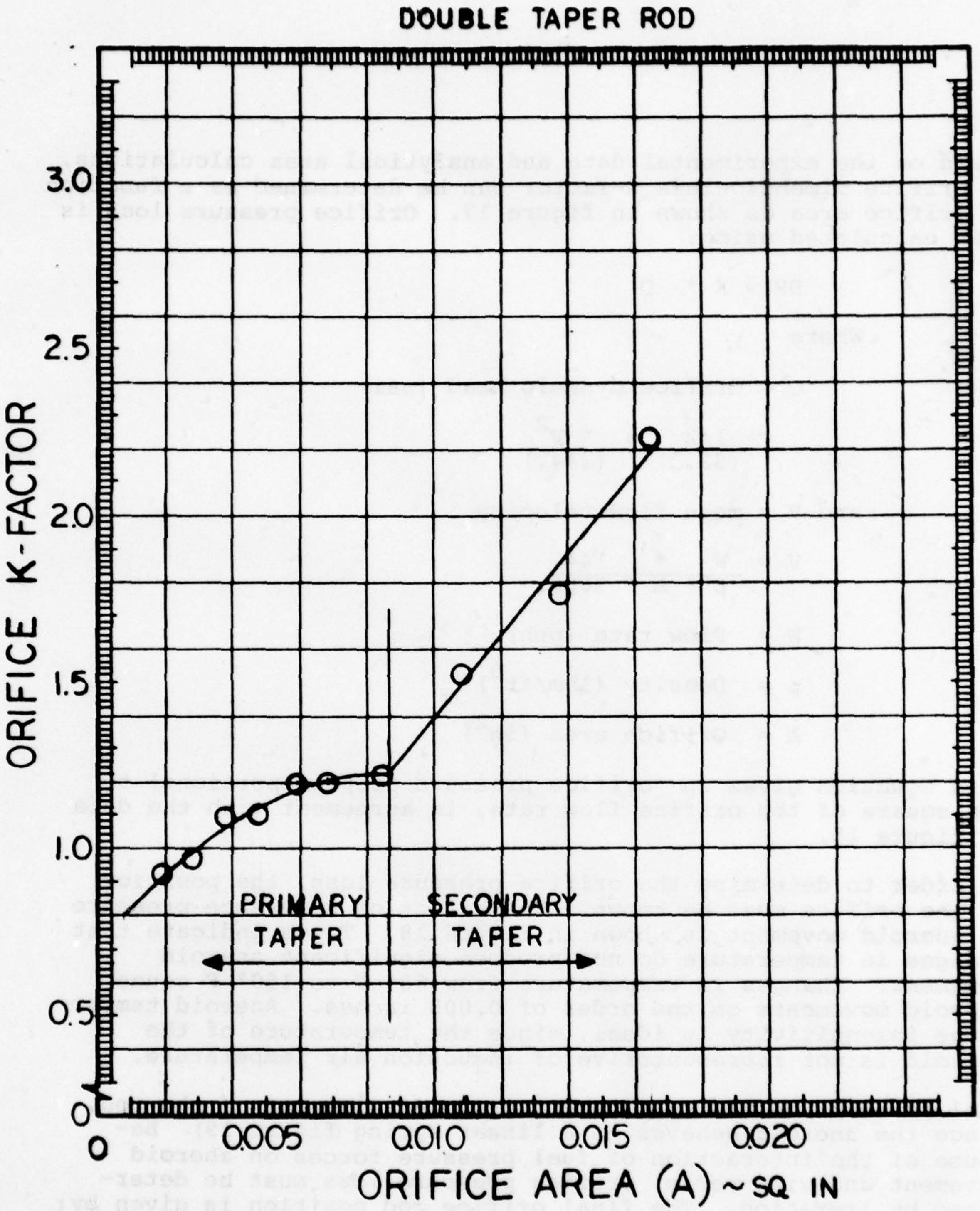


**FIGURE 17. VARIABLE ORIFICE LOSS FACTOR**

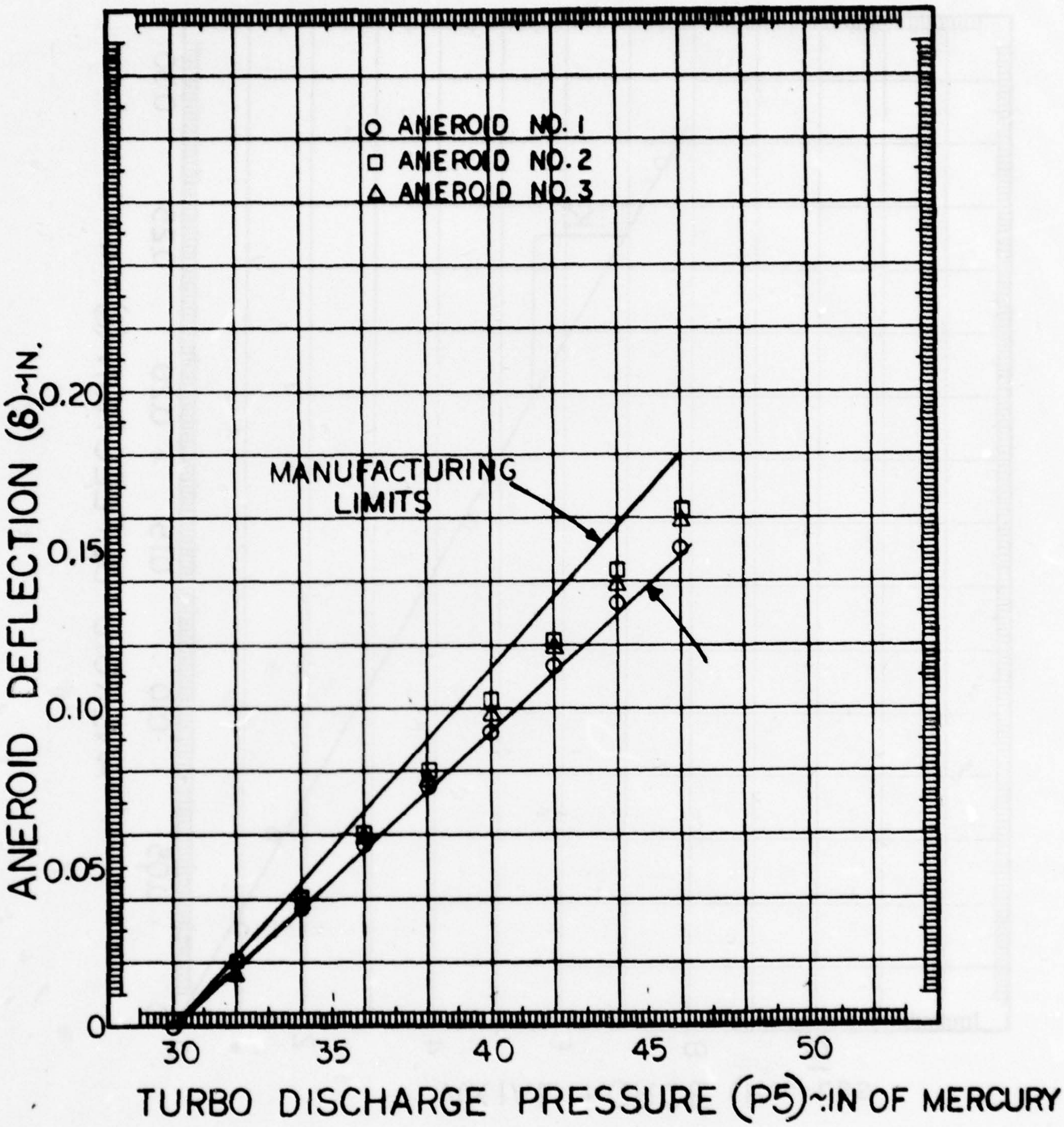


**FIGURE 18. ANEROID TEST RESULTS**

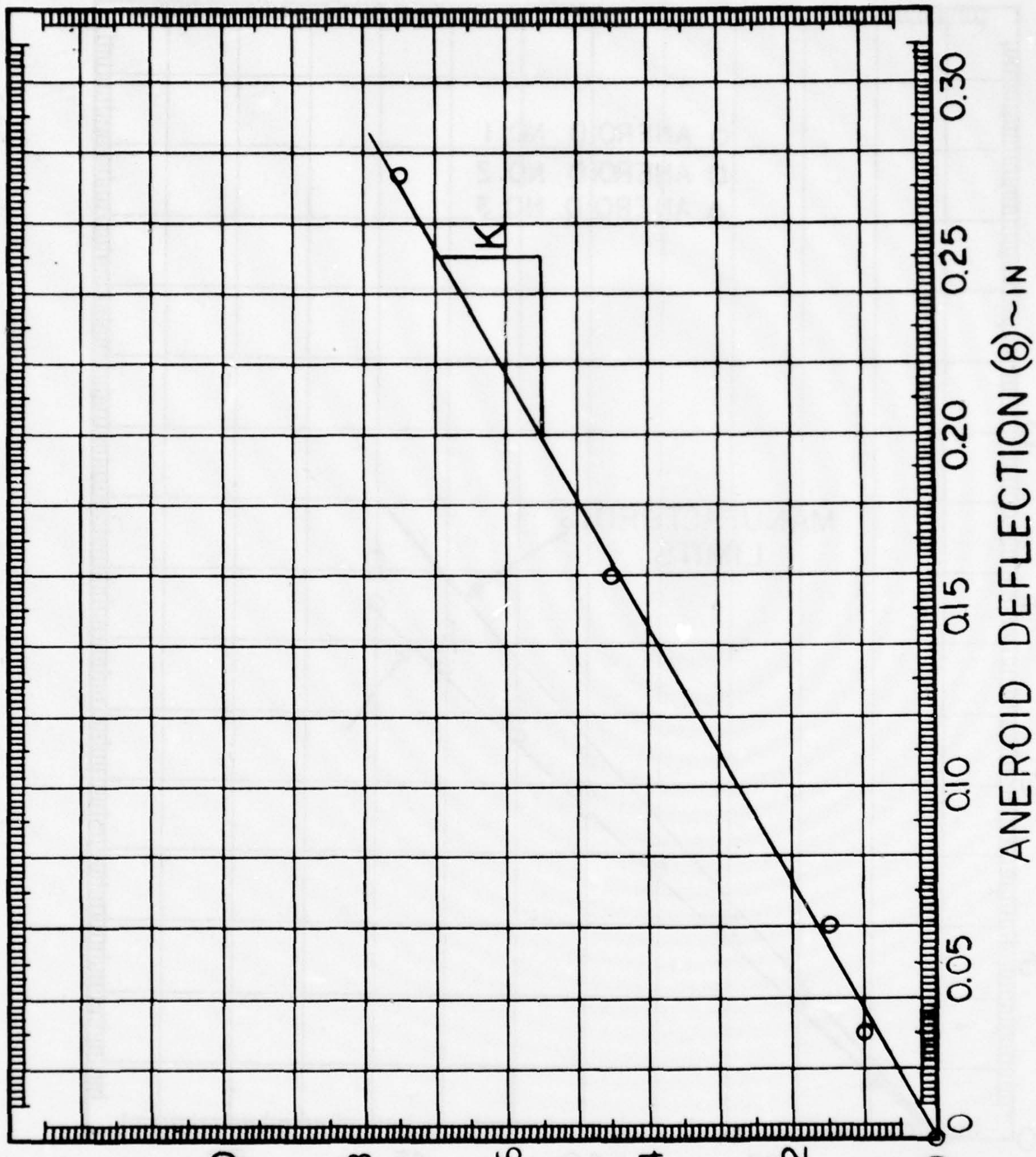


**FIGURE 19. ANEROID DEFLECTION DUE TO AXIAL FORCE**

$P_{adj}$ = Turbo discharge pressure when orifice was adjusted

$P_5$ = Turbo discharge pressure for present operating conditions

AMS = Slope of aneroid movement versus pressure (figure 18)

K = Spring constant of the aneroid (figure 19)

RF = Fuel pressure force on variable orifice rod

Orifice position ($\delta$) as obtained from equation 14 is zero when the orifice if full closed (see figure 16).

5) <u>Idle Relief Valve</u>
The idle relief valve is a spring-loaded valve used to set a minimum discharge pressure for the pump. A cross-sectional view of the relief valve is shown in figure 14. An adjustable spring and the action of the pump reference pressure (turbo discharge pressure, $P_5$) on the valve diaphragm act to close the valve. The fluid pressure of the Avgas is higher at the valve inlet than at the valve discharge, producing a force across the valve orifice (Av) which tends to open the valve. Static equilibrium of forces on the valve yields equation 15 for the valve pressure drop:

$$\Delta P_v = \frac{K_s * \Delta LS + (P5-Pds)Ae}{Av} \qquad (15)$$

Where $\Delta Pv$ = Valve pressure drop $(Lb_f/in^2)$

Av = Valve flow area $(in^2)$

Av = $\pi Rl^2$

Rl = Valve orifice radius (0.31 inches)

P5 = Turbo discharge pressure $(Lb_f/in^2)$

$P_{ds}$ = Valve downstream pressure $(Lb_f/in^2)$

Ae = Diaphragm effective area (sq in)

Ks = Valve spring constant $(Lb_f/inch)$

$\Delta LS$ = Ground-adjusted spring compression (inch)

Note that the valve pressure drop is independent of flow rate. This was found to be true from testing and is due to the rather large orifice area and relatively weak valve spring (low spring constant, Ks). A small movement of the valve provides sufficient flow area for the required bypass flow (at relatively low pressure drop across the valve). Increase of the spring force due to this movement is small compared to the initial spring force typical of correct idle adjustment.

The unknown constants in equation 15 were determined from bench tests. Partial differentiation of this equation at constant turbo discharge and valve exit pressure gives:

$$\frac{d\,(\Delta Pv)}{d\Delta LS} = \frac{Ks}{Av} \quad \text{(P5 and Pds Constant)}$$

which is the slope of the pressure drop versus spring adjustment curve given in figure 20. From the slope of the curve and known valve area, the spring constant was determined to be 13.7 $lb_f$/inch.

Simularily, the effect of turbo discharge pressure on valve pressure drop at constant spring load and valve exit pressure can be expressed as:

$$\frac{d\,(\Delta Pv)}{d\ P5} = \frac{Ae}{Av} \quad \delta\text{adj and Pds Constant)}$$

which is the slope of the line of data in figure 21. From the slope of the curve and known valve area, the diaphragm effective area was determined to be 0.334 $in^2$. With the constants determined from bench tests, equation 15 can be used to calculate the relief valve pressure drop.

6) Vapor Separator

The vapor separator pressure/flow relationship was determined experimentally and is given in figure 22. The internal passage connecting the pump discharge and inlet to the vapor separator was blocked and tapped to measure vapor separator flow rate. Flow rate was found to be insensitive to small changes in pump inlet pressure or vapor separator back pressure. Figure 22 was built into the computer model using a data block with linear inter polation between data points.

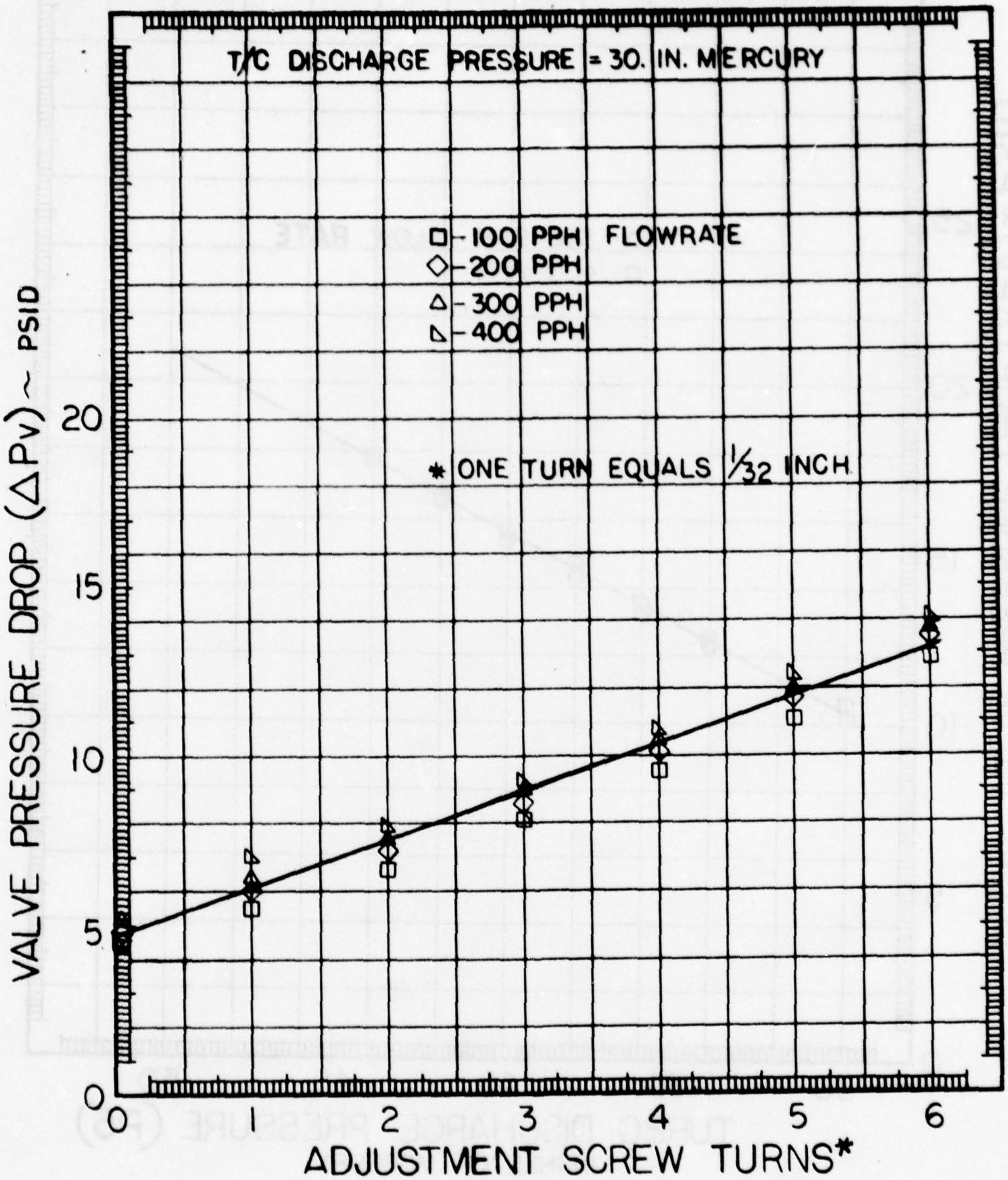


**FIGURE 20. EFFECT OF RELIEF VALVE ADJUSTMENT ON VALVE PRESSURE LOSS**

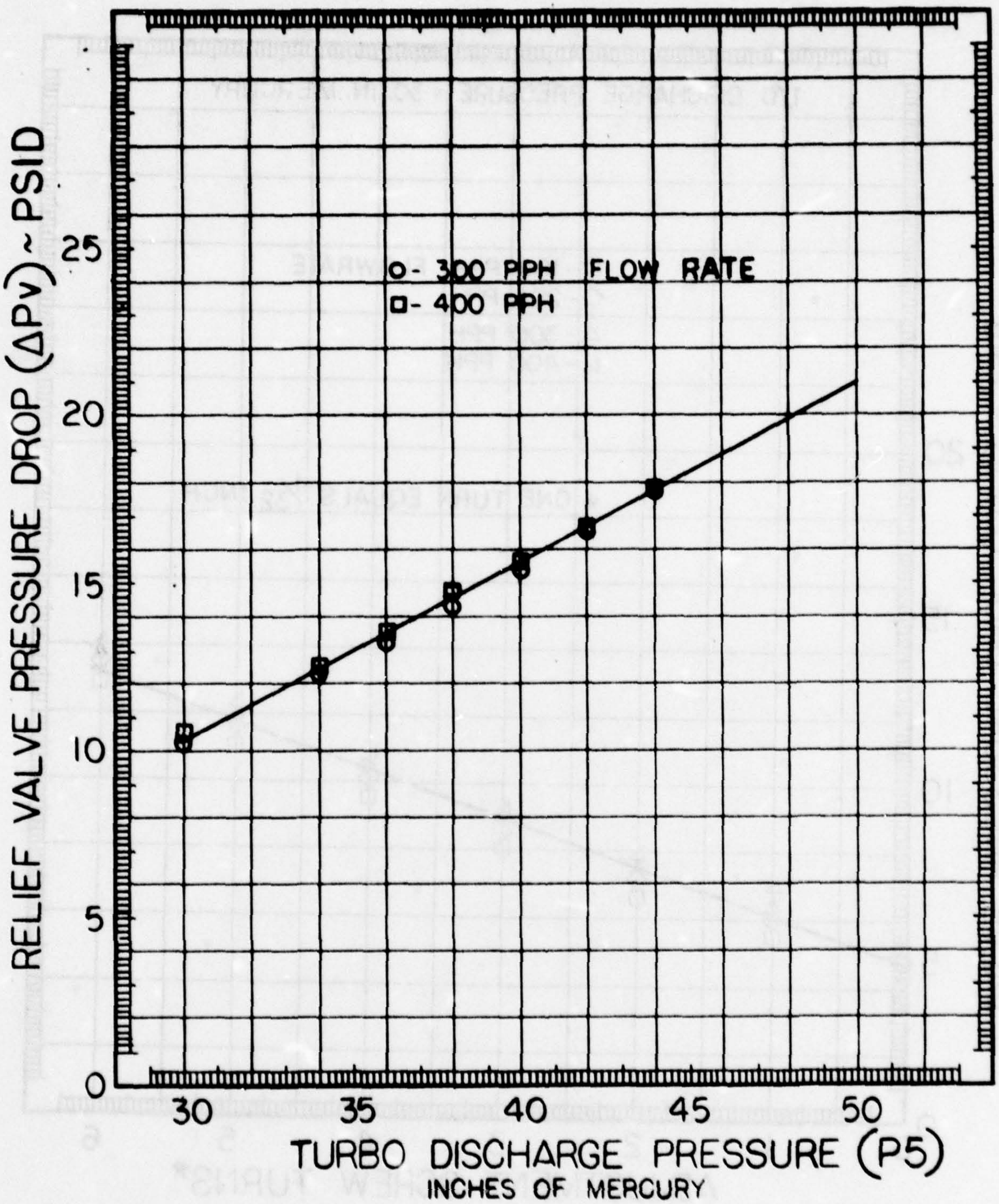


**FIGURE 21. EFFECT OF TURBO DISCHARGE PRESSURE ON RELIEF VALVE**

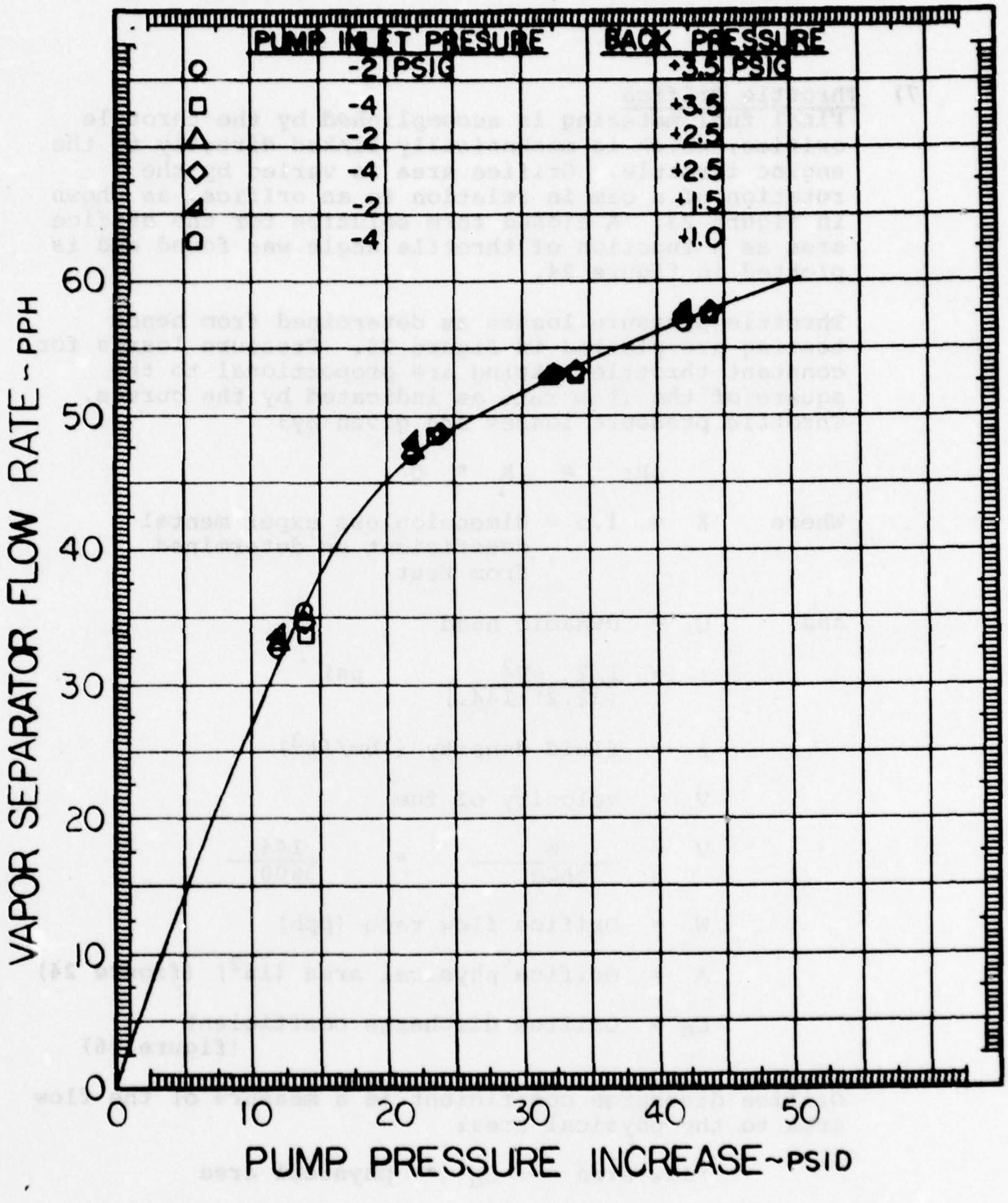


**FIGURE 22. VAPOR SEPARATOR FLOW RATE**

7) <u>Throttle Orifice</u>

Final fuel metering is accomplished by the throttle orifice, which is mechanically linked directly to the engine throttle. Orifice area is varied by the rotation of a cam in relation to an orifice, as shown in figure 23. A closed form solution for the orifice area as a function of throttle angle was found and is plotted in figure 24.

Throttle pressure losses as determined from bench testing are plotted in figure 25. Pressure losses for constant throttle setting are proportional to the square of the flow rate as indicated by the curves. Throttle pressure losses are given by:

$$\Delta Pt = K * Q$$

Where $K = 1.5 =$ dimensionless experimental coefficient as determined from test

and $Q =$ *dynamic head*

$$= \frac{1/2 \quad \rho V^2}{(32.2)(144.)} \quad \text{psi}$$

$\rho =$ fluid density ($lbm/ft^3$)

$V =$ velocity of fuel

$$V = \frac{W}{\rho A C_d} * \frac{144.}{3600.}$$

$W =$ Orifice flow rate (pph)

$A =$ Orifice physical area ($in^2$) (figure 24)

$C_d =$ Orifice discharge coefficient (figure 26)

Orifice discharge coefficient is a measure of the flow area to the physical area:

Flow area $= C_d$ * physical area

Figure 26 gives the experimentally determined discharge coefficient for the throttle orifice as a function of orifice physical area.

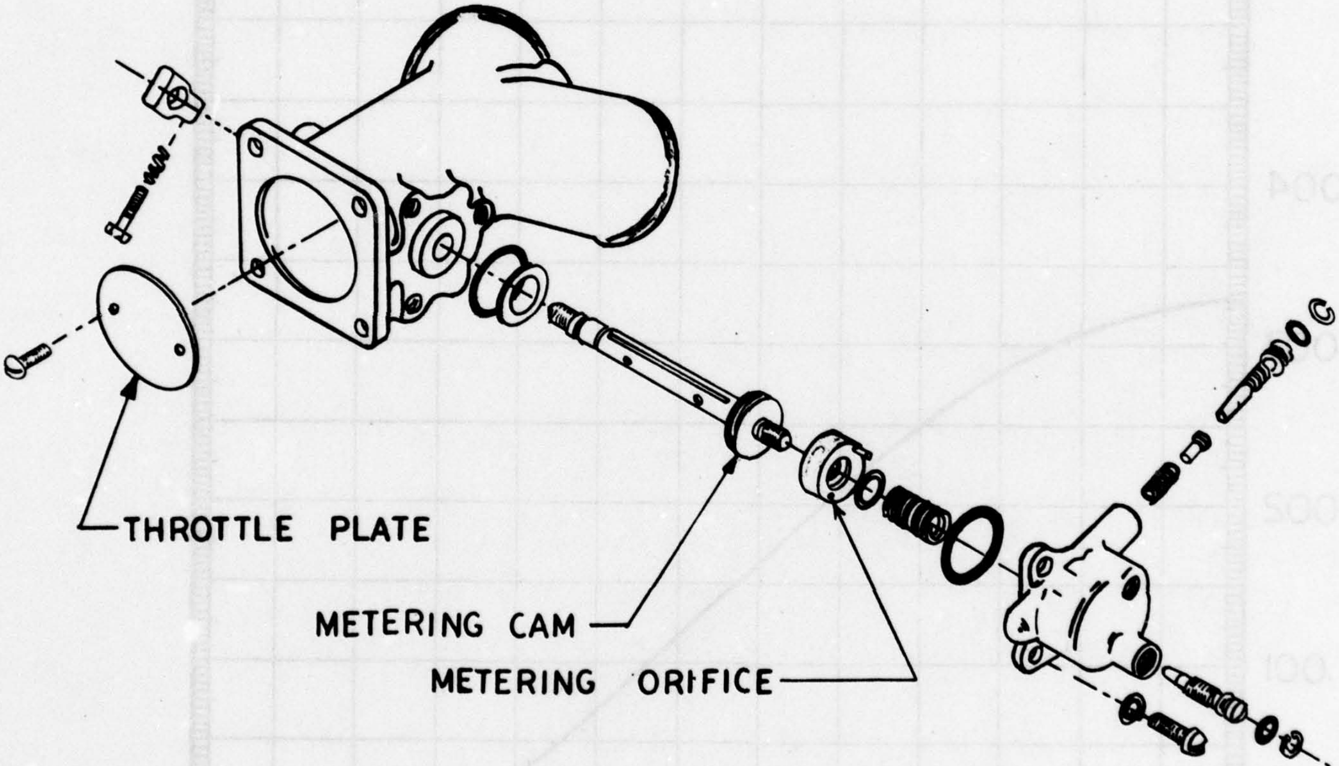


**FIGURE 23. AIR THROTTLE AND FUEL METERING ASSEMBLY**

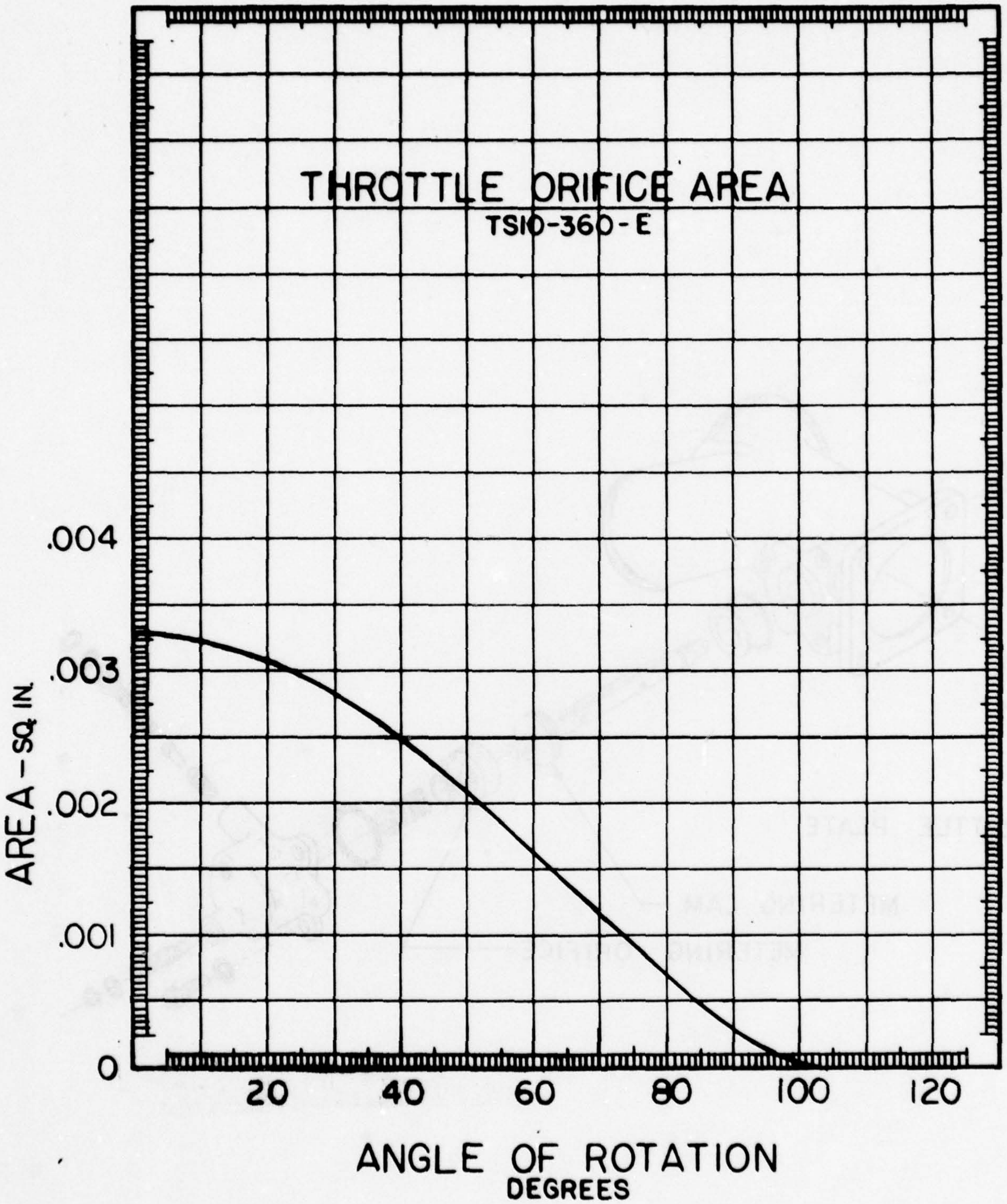


**FIGURE 24. THROTTLE ORIFICE AREA**

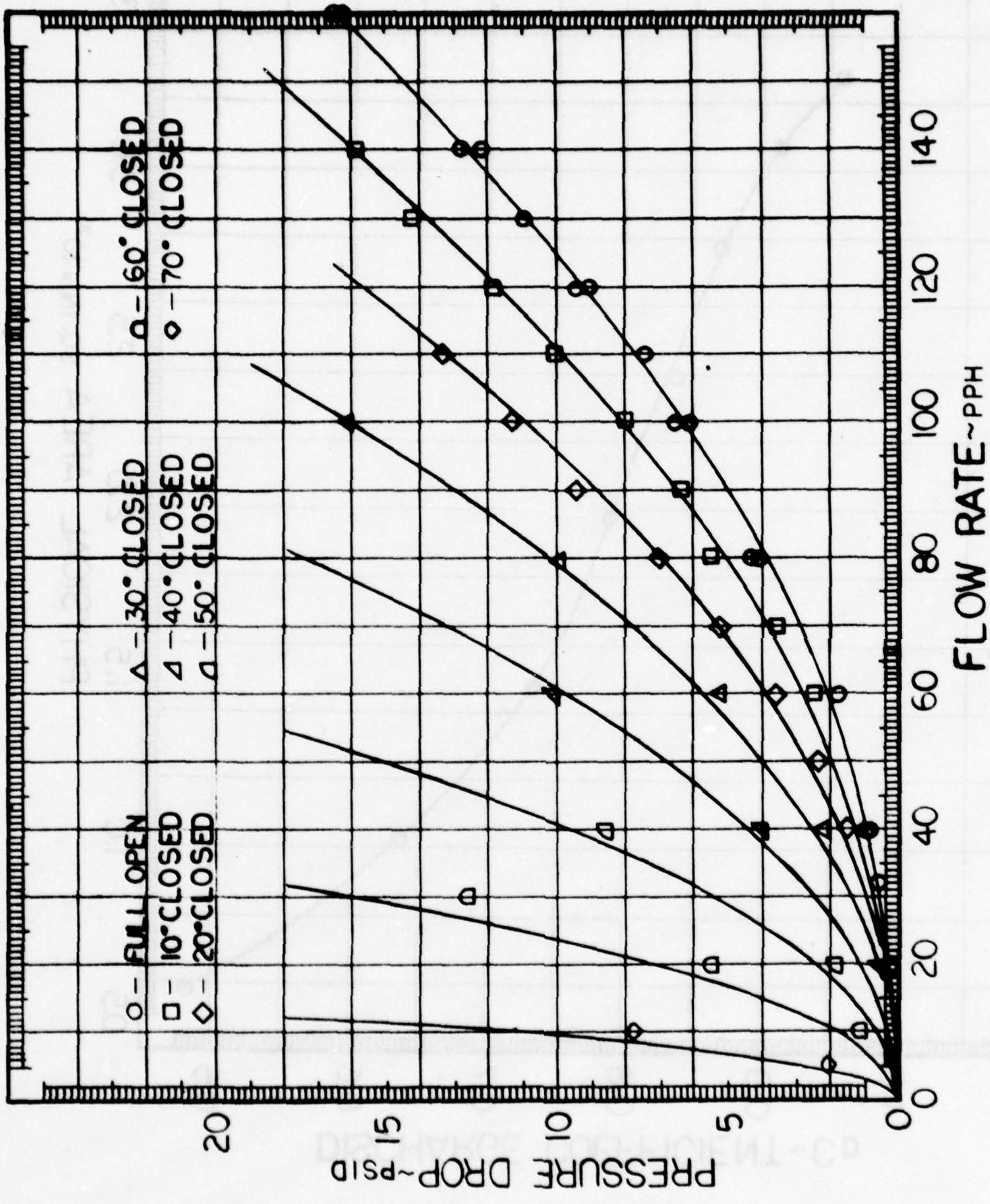


FIGURE 25. THROTTLE ORIFICE PRESSURE LOSS

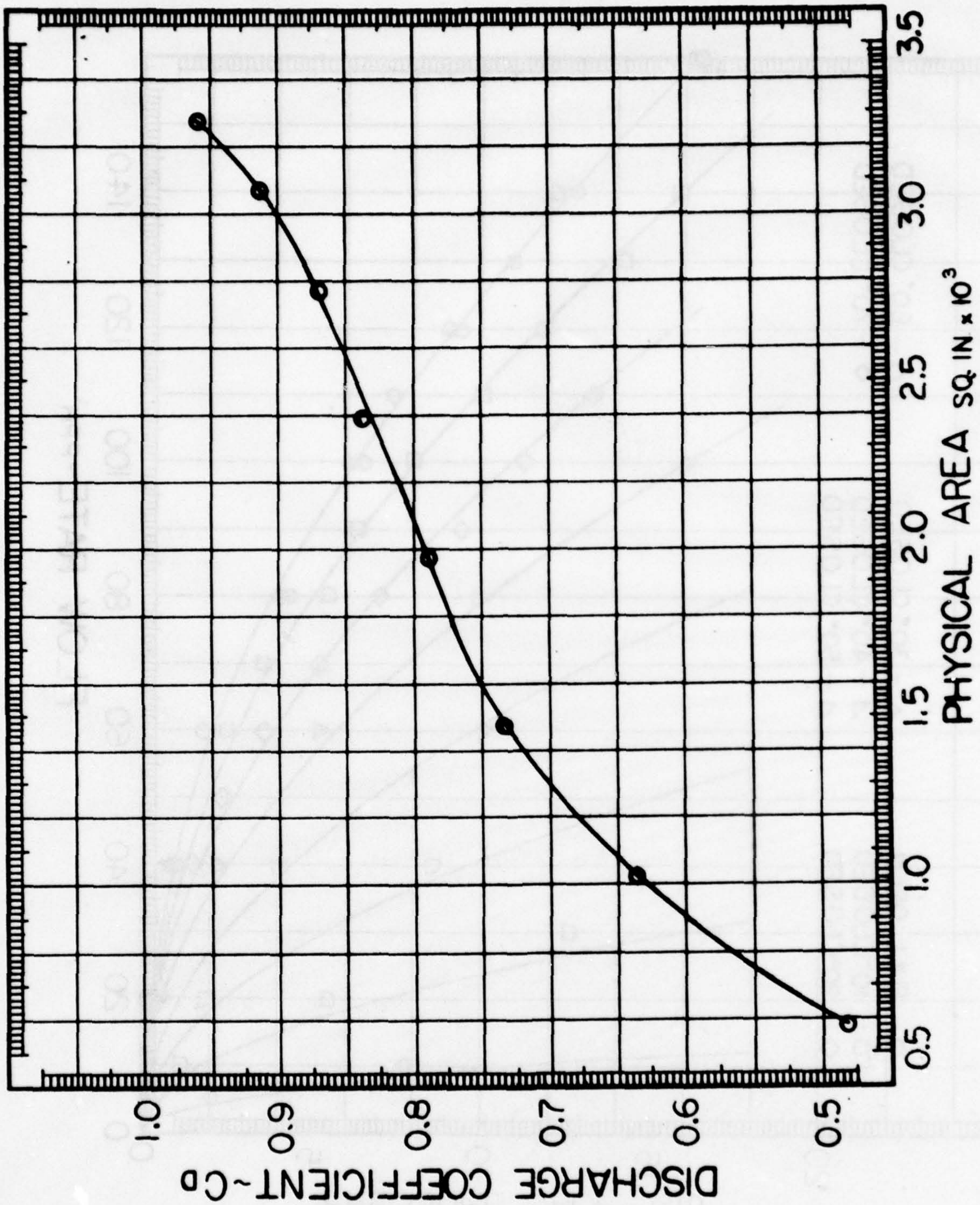


**FIGURE 26. THROTTLE ORIFICE DISCHARGE COEFFICIENT**

8) <u>Manifold Valve and Nozzles</u>

The manifold valve, nozzle lines and nozzles are factory calibrated as a unit. Figure 27 gives the relationship between fuel flow and metered pressure. Metered fuel pressure is defined as the difference between fuel pressure at the manifold inlet and nozzle reference (turbo discharge) pressure. Fuel flow through the nozzle was found to be independent of manifold pressure. Turbo discharge pressure is fed to the fuel jet as shown in figure 28 and prevents manifold pressure from affecting fuel flow.

## Simulation Checkout

A number of comparisons between simulation predictions and test data were made to check the computer simulation. Fuel bench tests of the entire fuel system were made to generate data for comparison. When possible, the simulation was compared directly with recorded engine data. However, throttle angle is rarely recorded during engine tests, and the accuracy of the throttle readings are questionable. Bench tests of the complete fuel system were made to simulate engine data by matching engine speed, turbo discharge pressure, and metered fuel pressure as recorded during engine calibration testing (reference 6). Careful measurements of the throttle angle were then made for input to the simulation.

The simulation was first "trimmed," using the variable orifice adjustment corresponding to ground trim on the actual system. Figure 29 shows the manufacturer's recommended flow rate and pressure at high power, as a function of the variable orifice ground trim. The simulation was trimmed to the middle of the recommended bands for fuel flow, metered fuel pressure, and pump discharge pressure. Idle flow rate was trimmed by adjusting the idle relief valve to 7.1 pph at 700 rpm. Fuel pump discharge pressure at idle was 6.7 psig. Continental's spec idle trim is 6 to 8 pph at 700 rpm, with a pump pressure of 6.5 $\pm$ 0.25 psig.

After trimming, the simulation predictions were compared to test data. Figure 30 shows the simulation predictions (connected by solid line) compared to fuel bench test data. The engine conditions simulated on the fuel bench correspond to engine prop load conditions, with horsepower ranging from 20 to 100 percent of maximum continuous power. The difference between the predicted and measured flow rate is within the accuracy of the bench measurements. Pump discharge pressure agreed well with measured values.

The effect of turbo discharge pressure on fuel system output is

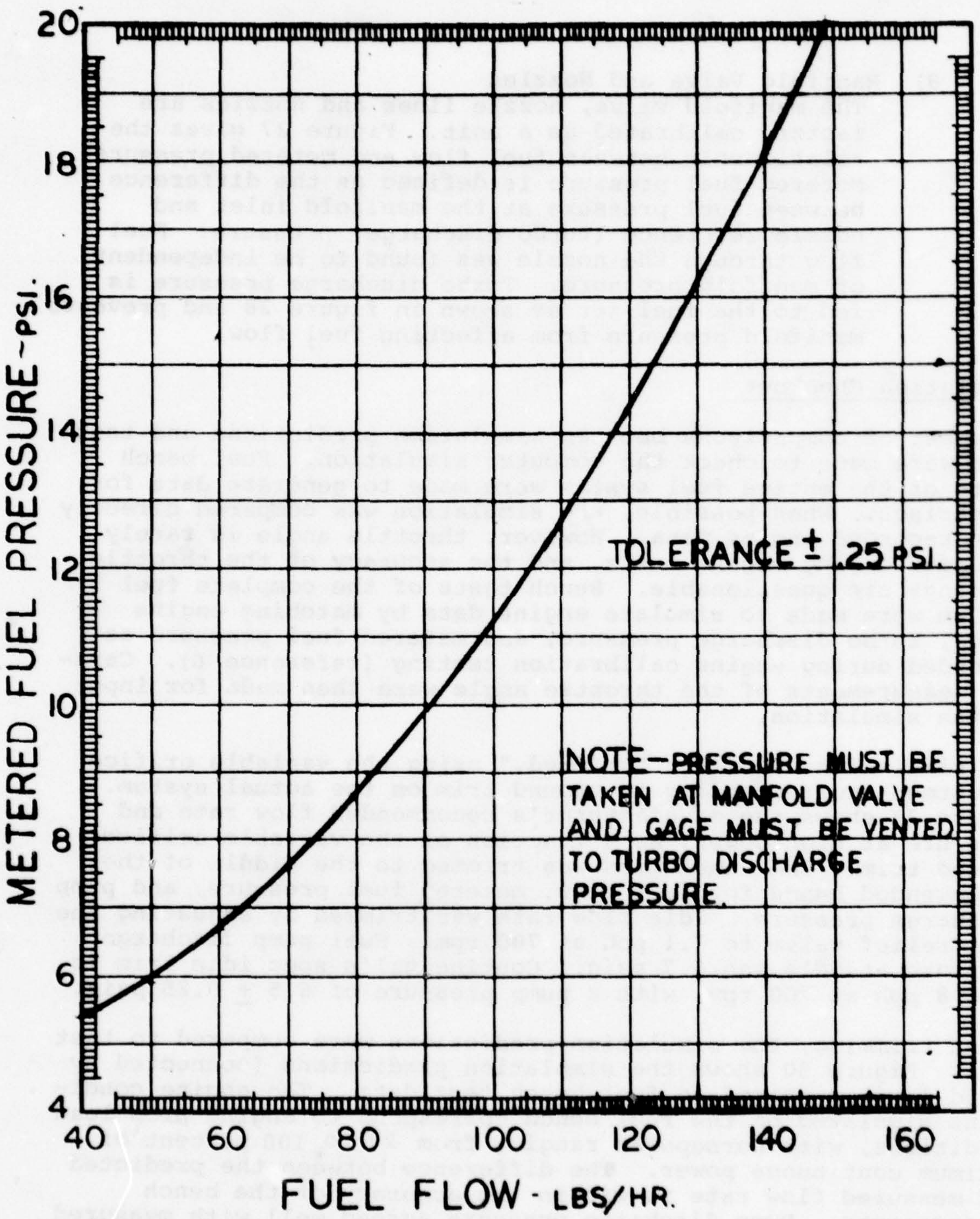


FIGURE 27. METERED FUEL ASSEMBLY CALIBRATION

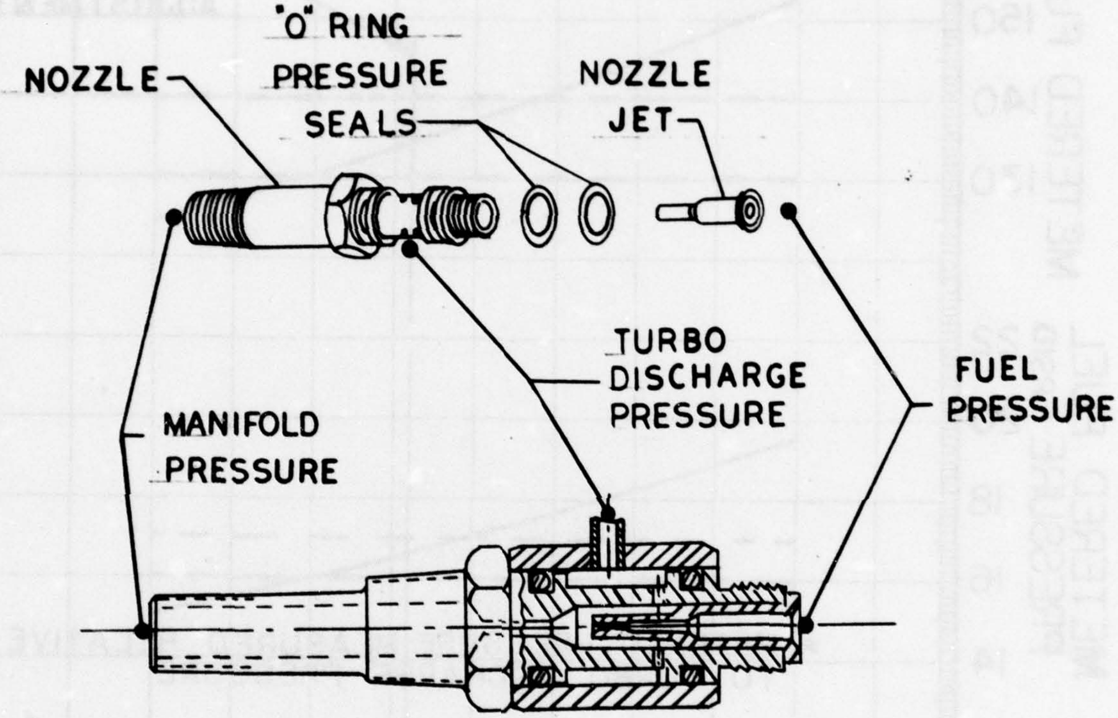


**FIGURE 28. FUEL NOZZLE DESIGN**

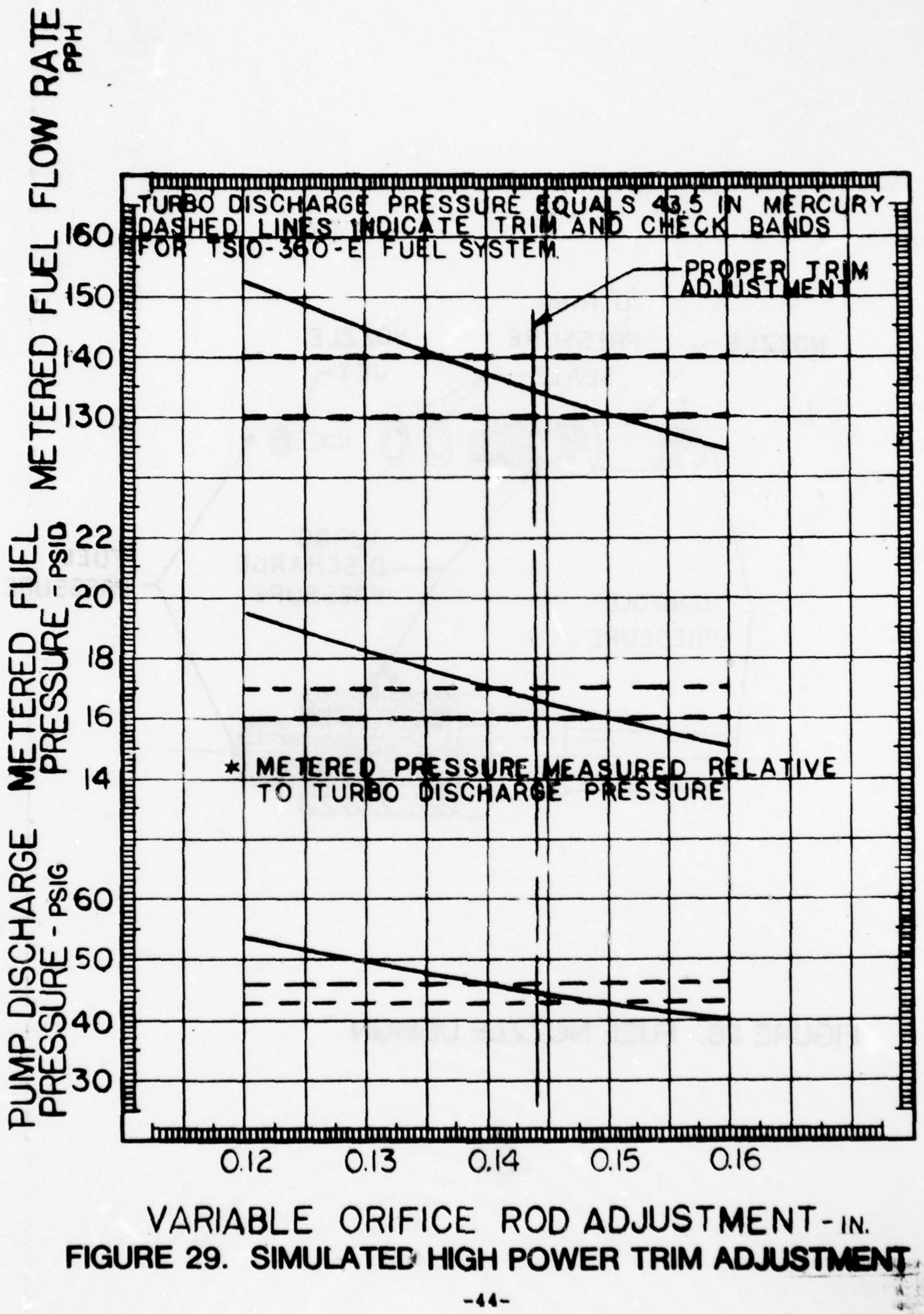


FIGURE 29. SIMULATED HIGH POWER TRIM ADJUSTMENT

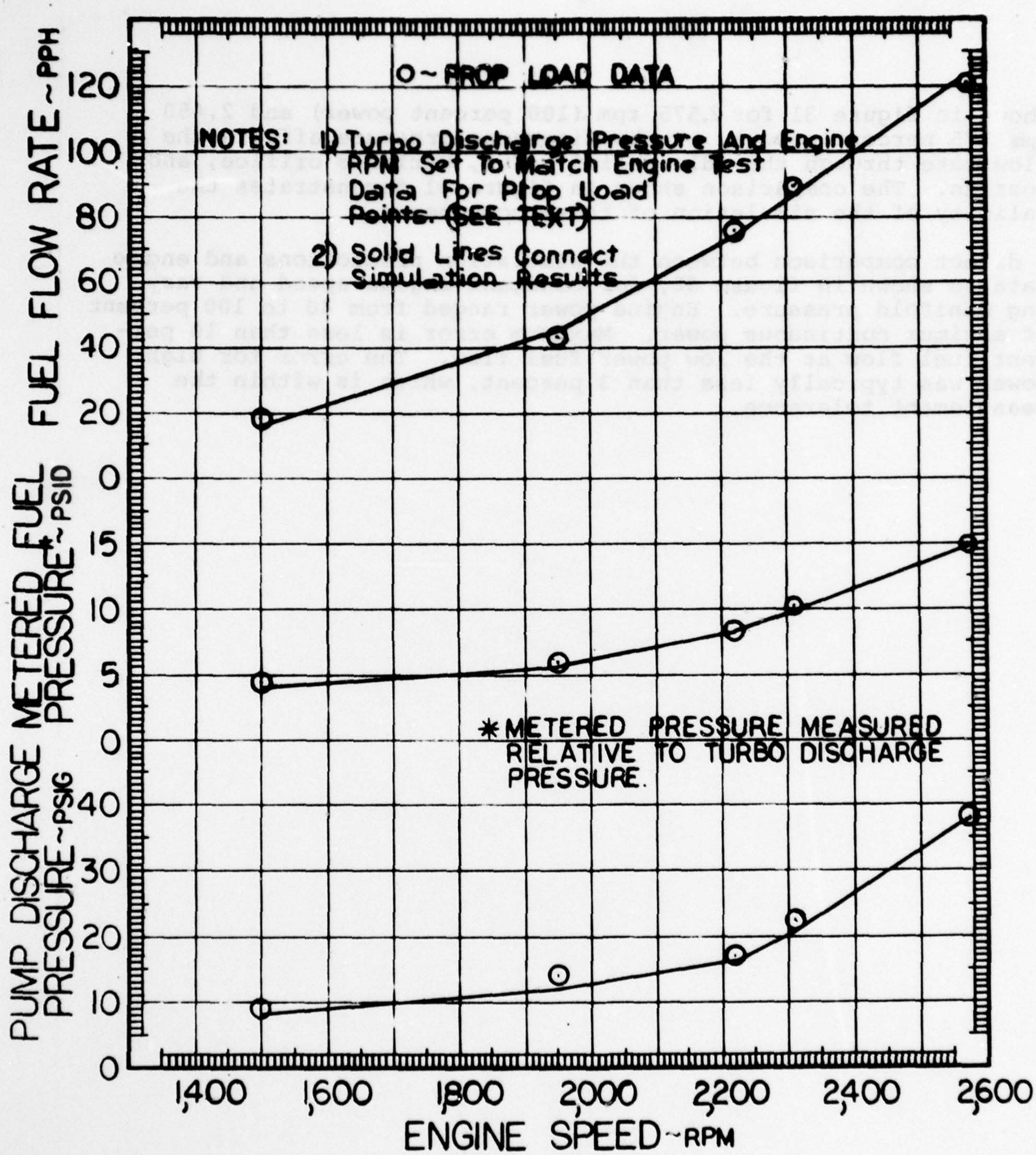


**FIGURE 30. COMPARISON OF FUEL SYSTEM SIMULATION WITH FUEL BENCH TEST DATA**

shown in figure 31 for 2,575 rpm (100 percent power) and 2,450 rpm (75 percent power). Turbo discharge pressure affects the flow rate through the idle relief valve, variable orifice, and nozzles. The comparison shown in figure 31 demonstrates the validity of the simulation of these components.

A direct comparison between the simulation predictions and engine data is shown in figure 32, for constant engine speed and varying manifold pressure. Engine power ranged from 40 to 100 percent of maximum continuous power. Maximum error is less than 10 percent fuel flow at the low power fuel flow. The error for high power was typically less than 3 percent, which is within the measurement tolerance.

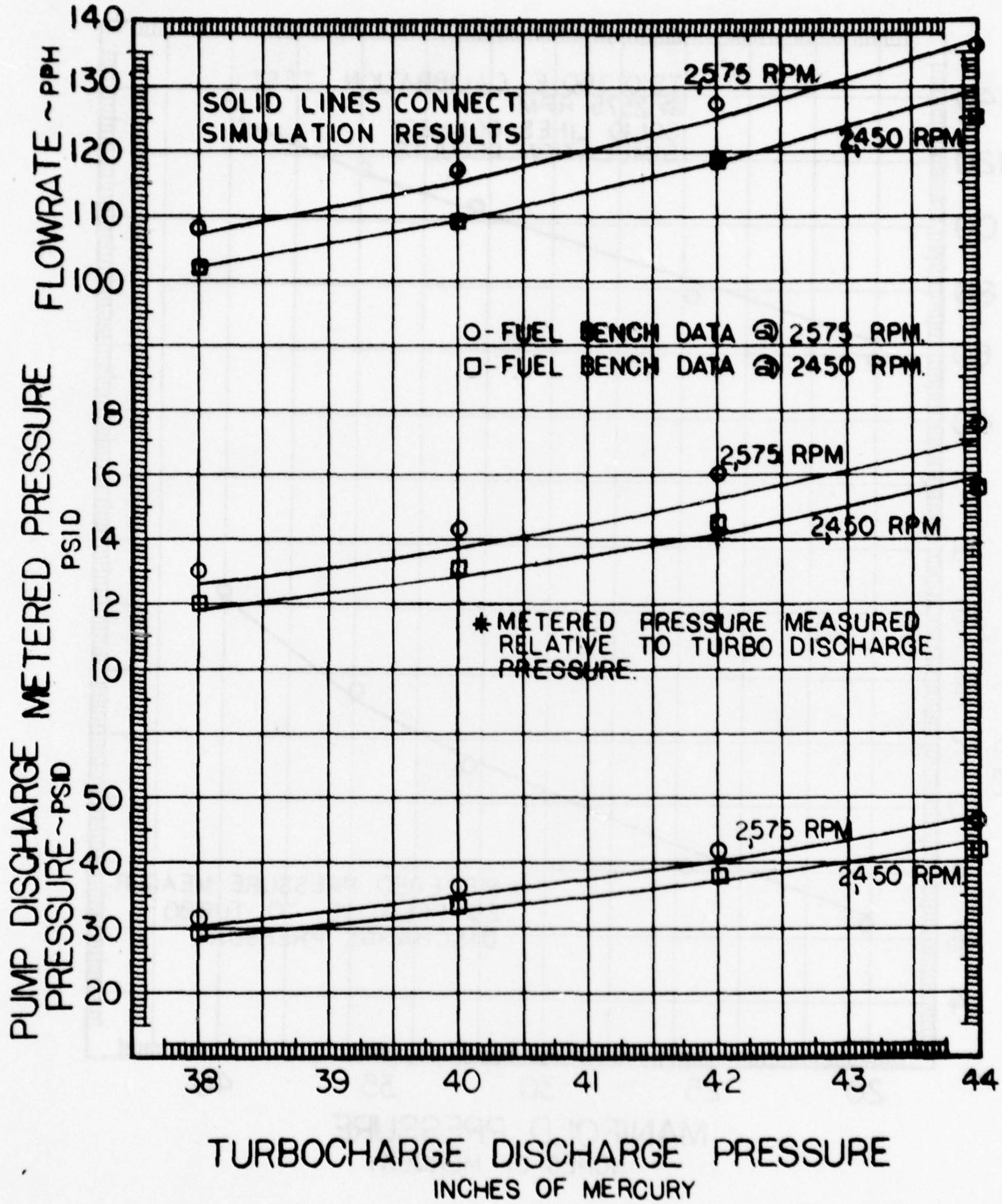


**FIGURE 31. COMPARISON OF FUEL SYSTEM SIMULATION WITH FUEL BENCH TEST DATA**

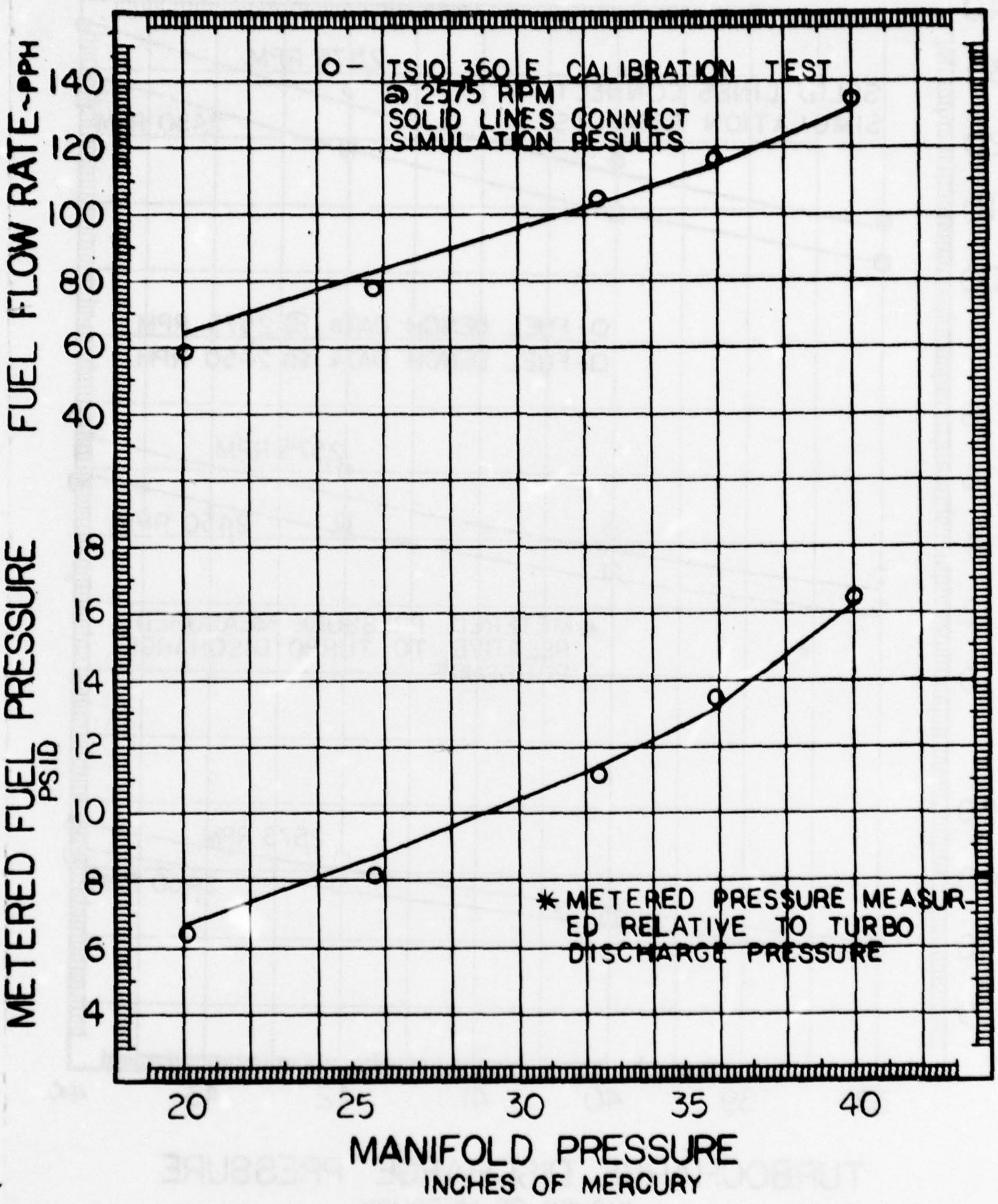


**FIGURE 32. COMPARISON OF FUEL SYSTEM SIMULATION WITH ENGINE CALIBRATION DATA**

## CONCEPTS TO IMPROVE FUEL INJECTION

During phase 1 of the contract, an investigation of the effects of leaning on engine emissions for the NAFEC seven-mode LTO cycle was completed. A review of this study was made to determine the reduction of emissions that could be expected for a TSIO-360-C engine, assuming a means of reducing the engine acceleration lean limit could be found. Table 1 repeats the information for the baseline emissions of the engine reported in reference 1, and shows hydrocarbons to be 212 percent of the proposed standards. Emissions of carbon monoxide and oxides of nitrogen were found to be 193 percent and 9 percent of the proposed standards, respectively. Table 1 also shows the emissions predicted provided the engine acceleration lean limit was reduced to 0.065 fuel/air ratio at low power. These predictions, based on the results found in phase I of the contract, show that the hydrocarbon emissions would be reduced from 212 percent to 48 percent of the proposed EPA standards. Carbon monoxide emissions would be reduced to 140 percent of the EPA standards, and emissions of nitrogen oxides would remain below the EPA standards, increasing to 46 percent. Take-off and climb fuel flows were assumed to be mean values (baseline flows) within the current fuel flow band. These high power conditions are engine temperature limited and the engine must be cooled with sufficient fuel as determined by flight testing a particular installation. The target value of 0.065 fuel/air ratio was picked as a value obtainable by modifying the current Continental fuel system and air intake manifold. Continental engines have demonstrated acceptable acceleration below 0.065 fuel/air ratio with more sophisticated fuel systems and intake manifolds.

Some methods for reducing the engine lean limit for acceleration and improving fuel/air ratio control are given below. The transient response of the turbocharger discharge pressure and flow rate during acceleration must be known in order to tailor the fuel system response to sensed parameters.

1) Temperature Compensation

The current fuel system has no means of temperature compensation. This means the fuel system must be adjusted for acceptable engine acceleration at the lowest expected ambient temperature. The effect of ambient temperature on fuel/air ratio for constant fuel flow is shown in figure 33. Given a minimum fuel/air ratio acceleration limit at 0° F, increasing ambient temperature increases the operating fuel/air ratio. Temperature compensation can be added to the Continental system using a N-Propyl Alcohol filled aneroid (figure 34). The aneroid movement necessary to maintain constant fuel/air ratio with varying

## TABLE I

## BREAKDOWN OF EMISSIONS BY ENGINE

## OPERATING CONDITION

## TSIO-360-C ENGINE

**All Values Are Percent of Proposed EPA Standards**

**HC EMISSIONS**

| Operating Condition | Baseline Emissions (%) | Leaned (1) Emissions (%) | Limit |
|---|---|---|---|
| Taxi | 154.5 | 10.5 | Accel |
| Idle | 24.0 | 11.0 | Accel |
| Climb | 20.4 | 20.4 | Temp |
| Approach | 11.9 | 4.9 | Accel |
| Take-off | 1.3 | 1.3 | Temp |
| Total | 212.1 | 48.1 | |

**CO EMISSIONS**

| Operating Condition | Baseline Emissions (%) | Leaned (1) Emissions (%) | Limit |
|---|---|---|---|
| Climb | 102.3 | 102.3 | Temp |
| Approach | 54.8 | 15.9 | Accel |
| Taxi | 26.4 | 12.3 | Accel |
| Take-off | 9.5 | 9.5 | Temp |
| Idle | Neg | Neg | Accel |
| Total | 193.0 | 140.0 | |

**NO EMISSIONS**

| Operating Condition | Baseline Emissions (%) | Leaned (1) Emissions (%) | Limit |
|---|---|---|---|
| Approach | 7.1 | 38.8 | Accel |
| Climb | 0.4 | 3.3 | Temp |
| Taxi | 0.7 | 1.9 | Accel |
| Idle | 0.6 | 2.0 | Accel |
| Take-off | Neg | Neg | Temp |
| Total | 8.8 | 46.0 | |

(1) Acceleration limit assumed to be reduced to 0.065 fuel/air ratio by improving manifold and fuel management.

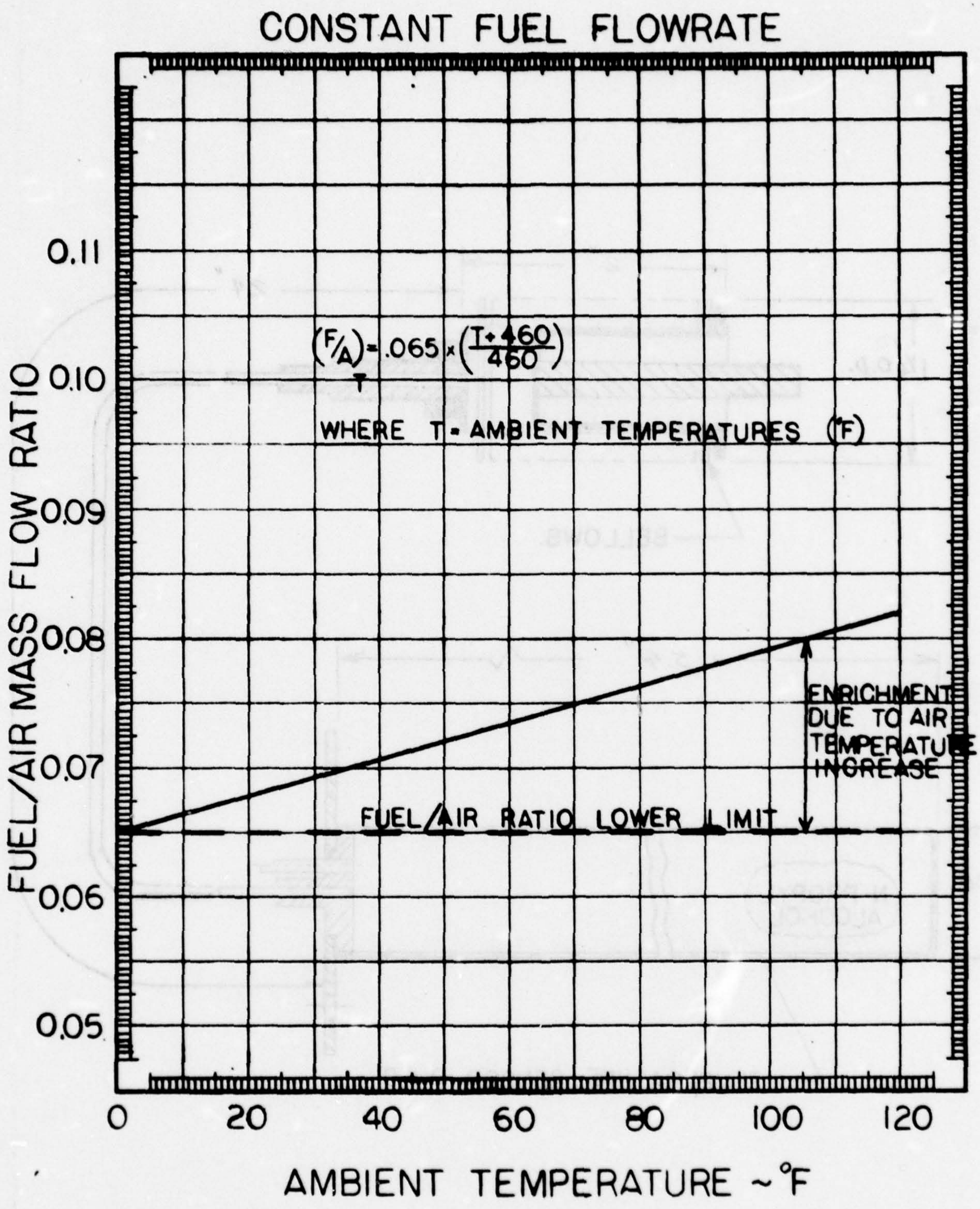


**FIGURE 33. EFFECT OF AMBIENT AIR TEMPERATURE ON ENGINE FUEL /AIR RATIO**

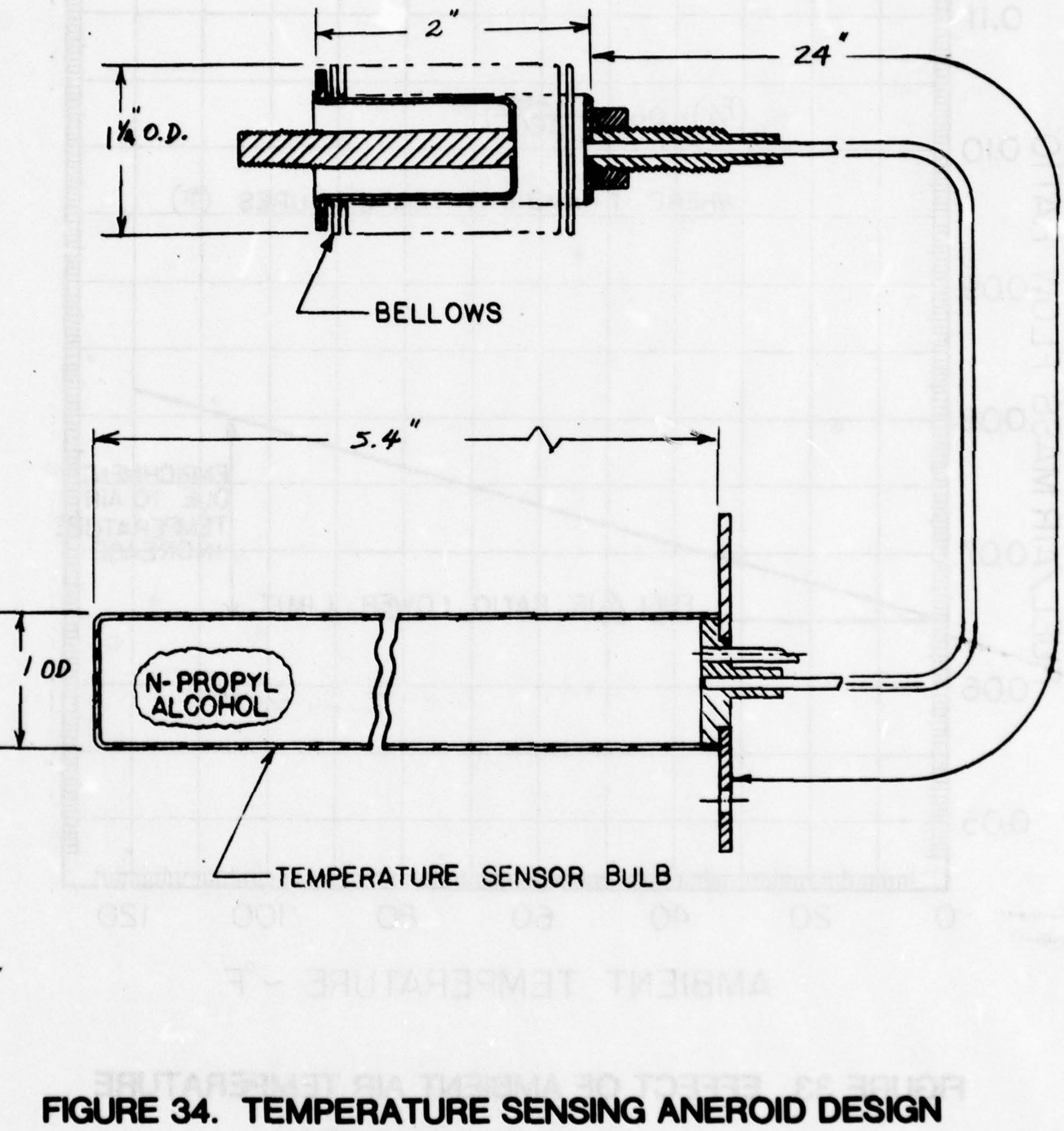


**FIGURE 34. TEMPERATURE SENSING ANEROID DESIGN**

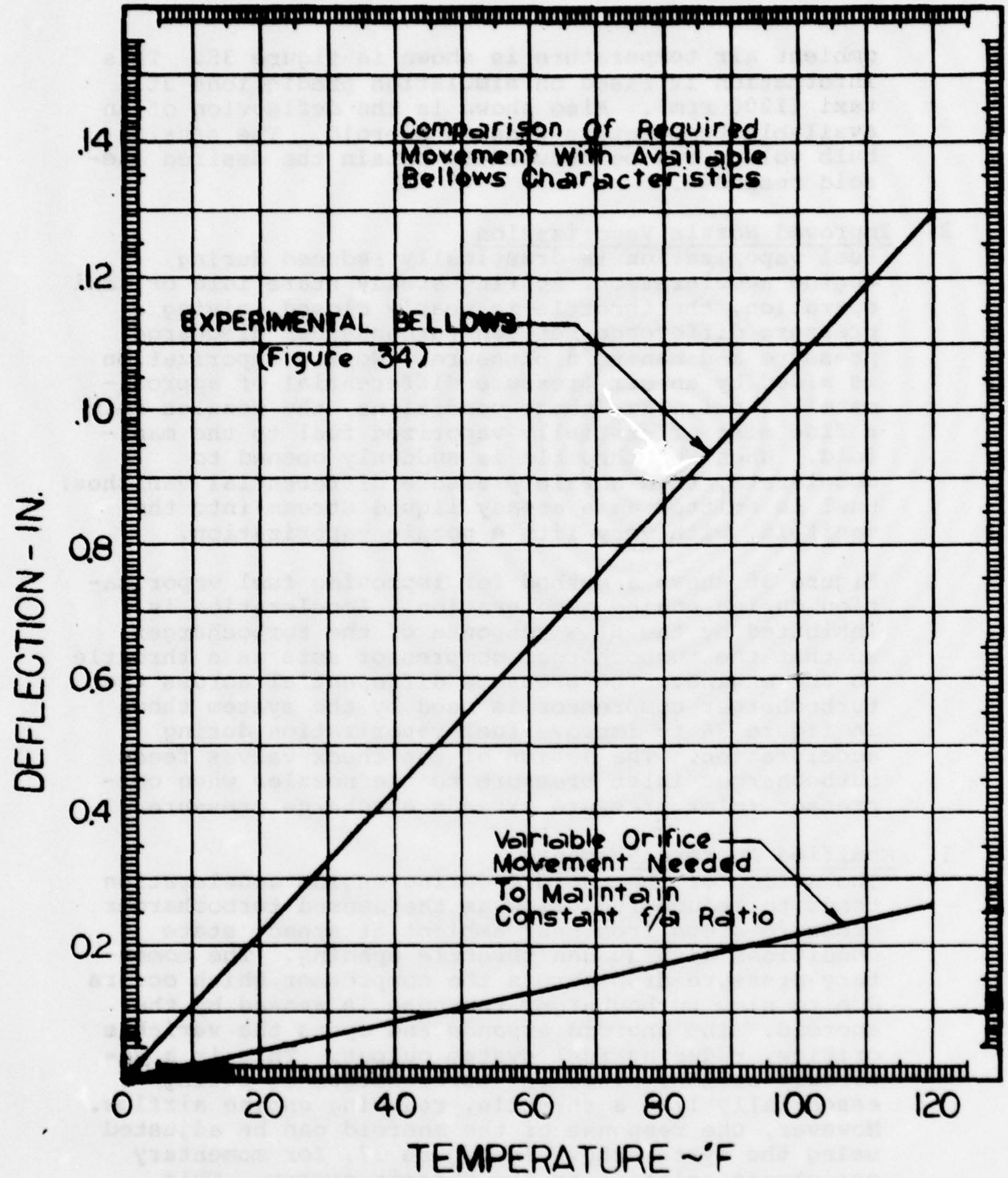


**FIGURE 35. BELLOWS MOVEMENT REQUIRED FOR TEMPERATURE COMPENSATION**

ambient air temperature is shown in figure 35. This information is based on simulation predictions at taxi (1200 rpm). Also shown is the deflection of an available temperature-sensing aneroid. The sensing bulb volume can be reduced to obtain the desired aneroid response.

2) Improved Nozzle Vaporization

Fuel vaporization is drastically reduced during engine acceleration. During steady state idle or taxi operation, the throttle is nearly closed, giving a pressure difference between turbocharger discharge pressure and manifold pressure. Nozzle vaporization is aided by an air pressure differential of approximately 5 psi. For these conditions, the nozzles emit a fine mist of partially vaporized fuel to the manifold. When the throttle is suddenly opened to accelerate, this nozzle pressure differential vanishes. Fuel is emitted as a steady liquid stream into the manifold, with very little nozzle vaporization.

Figure 36 shows a method for improving fuel vaporization during engine acceleration. Acceleration is inhibited by the slow response of the turbocharger, so that the turbocharger compressor acts as a throttle to the engine. The pressure differential across the turbocharger compressor is used by the system shown in figure 36 to improve fuel vaporization during acceleration. The action of the check valves feeds turbocharger inlet pressure to the nozzles when compressor inlet pressure exceeds discharge pressure.

3) Modified Aneroid Response

The action of the aneroid during engine acceleration tends to reduce fuel flow as the sensed turbocharger pressure drops from near ambient at steady state conditions with sudden throttle opening. The momentary pressure drop across the compressor which occurs due to slow turbocharger response is sensed by the aneroid. The aneroid expands and opens the variable orifice, reducing fuel system output. This is a desirable action, since the turbocharger is acting essentially like a throttle, reducing engine airflow. However, the response of the aneroid can be adjusted using the system shown in figure 37, for momentary enrichment relative to the current system. This could be used to counter the effects of leaning at steady state conditions, and thus reduce the acceleration lean limit. The probable response of such a system would be as shown qualitatively in figure 38.

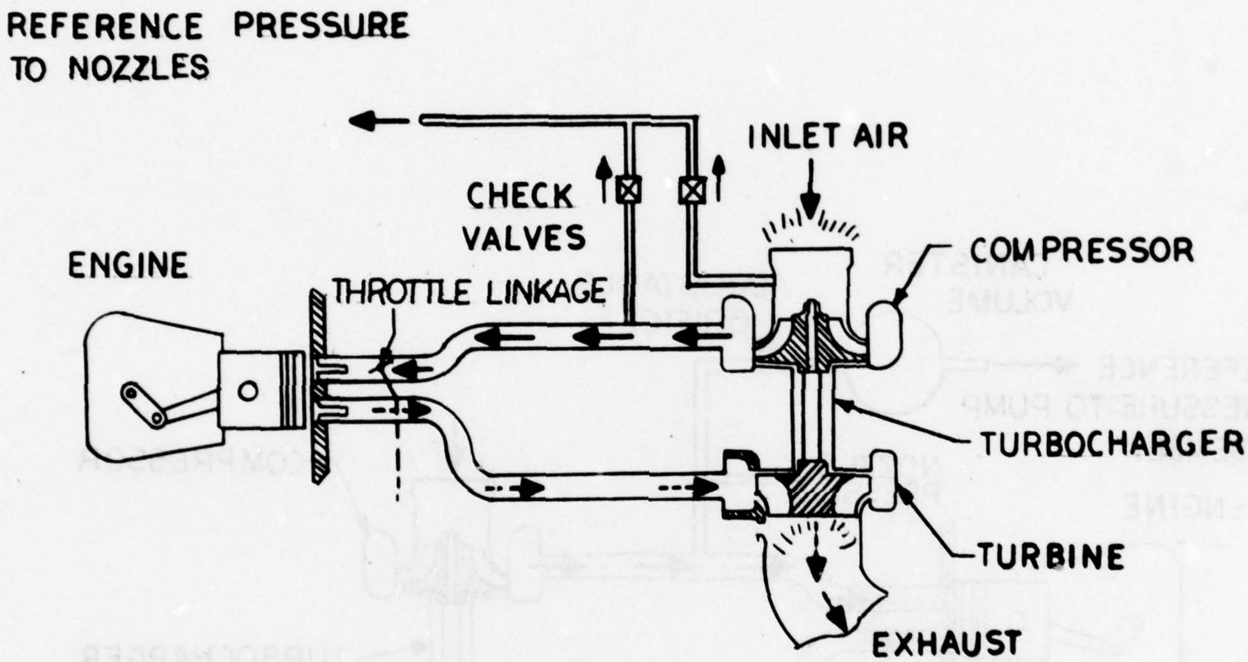


**FIGURE 36. FUEL SYSTEM MODIFICATION FOR IMPROVED FUEL VAPORIZATION DURING ACCELERATION**

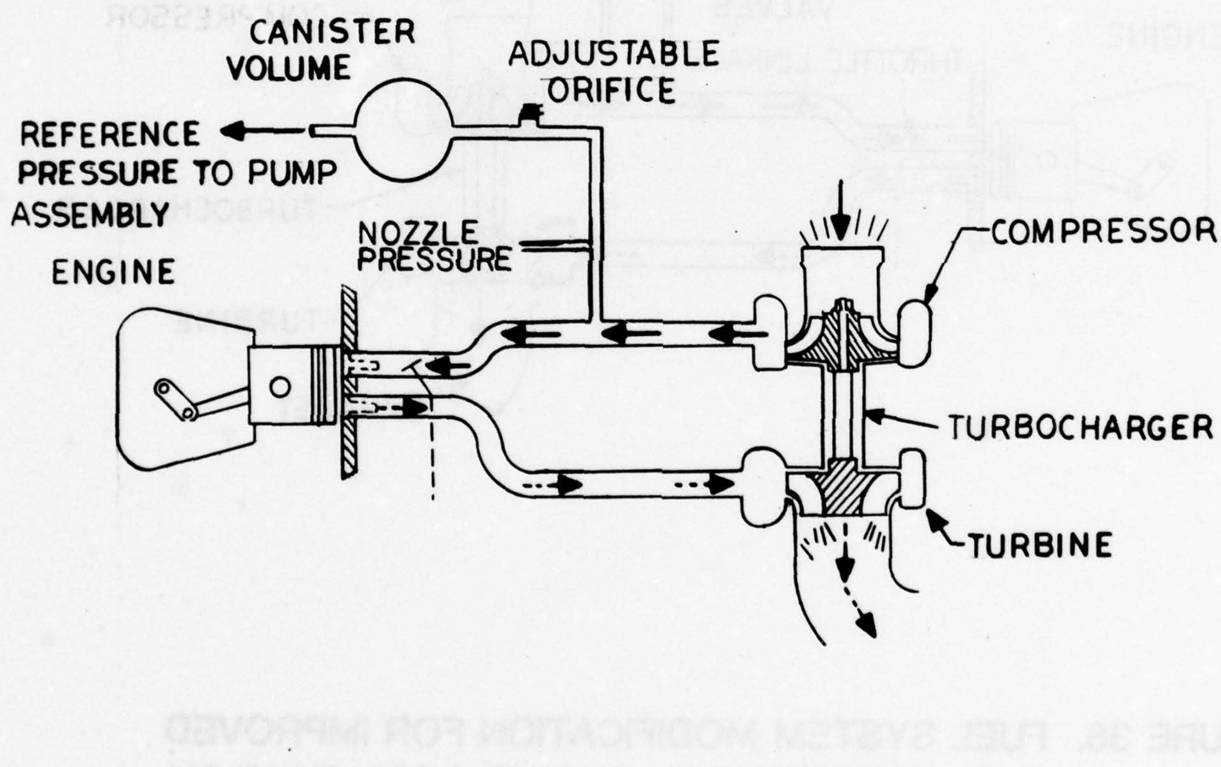


**FIGURE 37. FUEL SYSTEM MODIFICATION FOR OFF-IDLE ENRICHMENT DURING ACCELERATION**

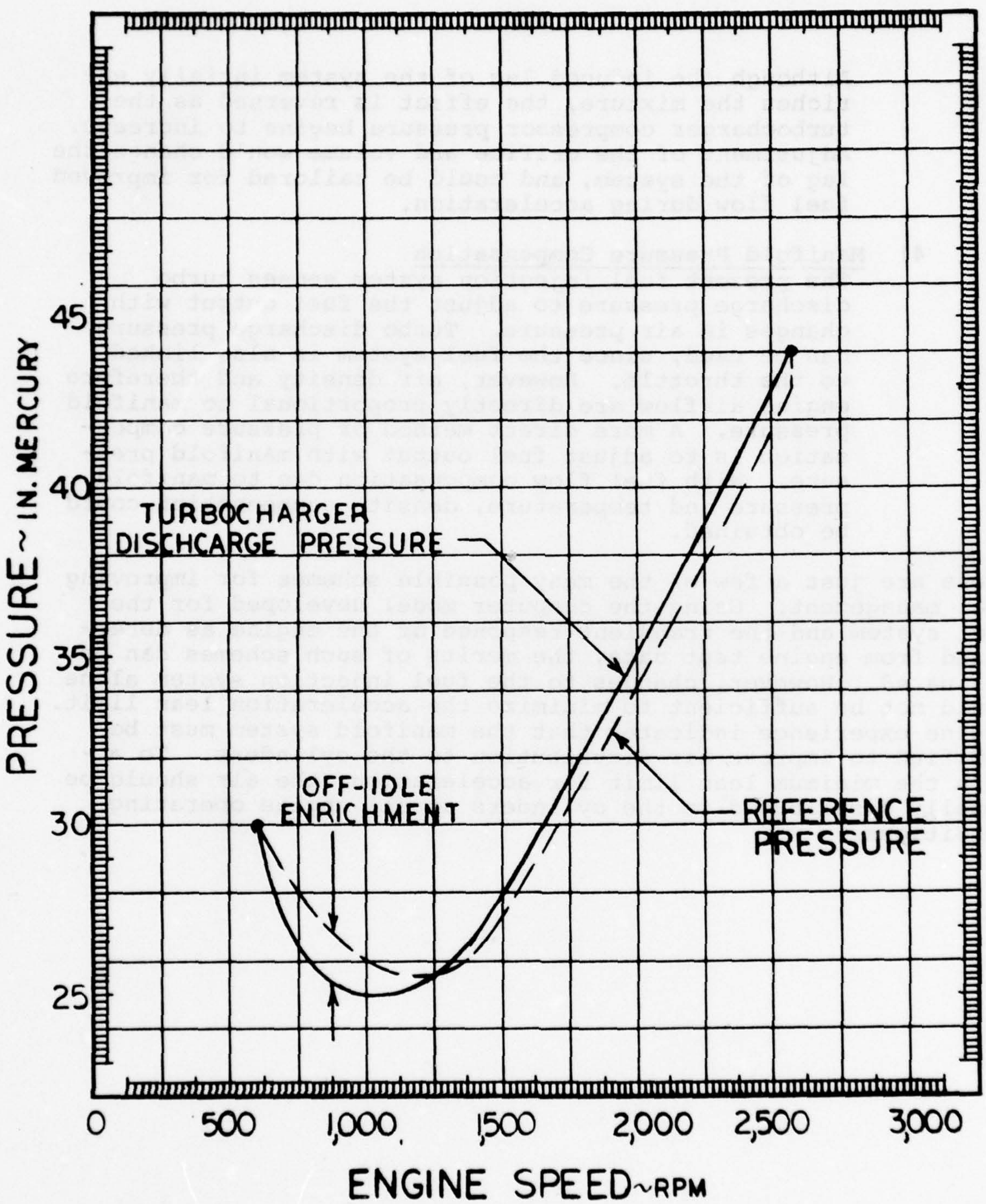


**FIGURE 38. DELAYED REFERENCE PRESSURE RESPONSE DURING ENGINE ACCELERATION**

Although the induced lag of the system intially enriches the mixture, the effect is reversed as the turbocharger compressor pressure begins to increase. Adjustment of the orifice and volume would change the lag of the system, and could be tailored for improved fuel flow during acceleration.

4) Manifold Pressure Compensation

The present fuel injection system senses turbo discharge pressure to adjust the fuel output with changes in air pressure. Turbo discharge pressure can be used, since the fuel system is also linked to the throttle. However, air density and therefore engine airflow are directly proportional to manifold pressure. A more direct method of pressure compensation is to adjust fuel output with manifold pressure. With fuel flow compensation due to manifold pressure and temperature, density compensation could be obtained.

These are just a few of the many possible schemes for improving fuel management. Using the computer model developed for the fuel system and the transient response of the engine as determined from engine test data, the merits of such schemes can be evaluated. However, changes to the fuel injection system alone would not be sufficient to minimize the acceleration lean limit. Engine experience indicates that the manifold system must be modified to improve air distribution to the cylinders. To attain the minimum lean limit for acceleration, the air should be equally distributed to the cylinders at all engine operating conditions.

# CONCLUSIONS

From the results, it is concluded that:

1) A computer simulation of the TCM fuel injection system has been developed which predicts accurately the fuel flow for the TSIO-360-E system. Changes in fuel flow due to varying engine conditions, ambient conditions, and fuel system adjustments can be predicted.

2) Reduced emissions and improved fuel economy at the full rich setting for cruise power and below can be attained by adding temperature compensation to the fuel system. Temperature compensation would reduce fuel flow for engine operation at high intake temperature.

3) Improved fuel management during acceleration along with better airflow distribution would reduce the acceleration lean limit and emissions in the aircraft landing and take-off (LTO) cycle. If modifications are sufficient to reduce the acceleration lean limit to 0.065 fuel/air ratio, hydrocarbon emissions can be reduced to 61 percent of the EPA emission standards for the NAFEC seven-mode LTO cycle. Carbon monoxide emissions would be reduced from 193 percent to 140 percent of the standards. Emissions of nitrogen oxides would remain below the standards at 46 percent.

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## APPENDIX

## OPERATING INSTRUCTIONS
## FOR
## TSIO-360-E FUEL INJECTION SYSTEM COMPUTER SIMULATION

Input to the computer simulation of the Continental TSIO-360-E fuel injection system consists of the engine operating conditions and fuel system adjustments necessary to establish the operating conditions of the system. A complete listing of the input is given in Table A-1. Several computer runs are necessary to establish the input values for valve positions required to simulate a particular fuel system trim. This process is analogous to the actual trimming of the fuel injection system. Two trims are required:

(1) Idle Trim. Computer runs are made simulating idle speed (700 rpm) and throttle position (72° from full open throttle) with several values for idle relief valve adjustment (SAL). These results can be used to determine the approximate relief valve setting required to give the desired idle pump discharge pressure (X2 minus ambient pressure, PAMB). This pressure is generally set to be 6.0 to 6.5 psig. Next, the idle fuel flow adjustment (ADJCU) is varied to establish the correct input to give the desired metered fuel pressure at idle. This pressure is calculated from the computer output for absolute metered fuel pressure (X3, psia) minus turbo discharge pressure (P5, psia), turbo discharge pressure at idle is normally equal to ambient pressure. Idle metered fuel pressure is generally set to be 3.5 to 4.0 psid (referenced to turbo discharge pressure).

(2) Full Power Trim. The simulation is next adjusted at full power (defined as 2575 rpm, 40. inches manifold pressure) using the variable orifice adjustment input. The throttle settings for full power can be determined from actual engine data. Correct full power throttle settings are specified by Continental as a function of density altitude. For engine ground trims, the exhaust waste gate is adjusted to obtain 40 inches of manifold pressure at a specified throttle setting. This full throttle set-

ing is a function of density altitude as specified in figure A-1. Using the full throttle setting (ALFA) as established from engine data or from figure A-1, the variable orifice position (ADJVO) is varied to obtain the desired metered fuel pressure (X3 minus P5) or metered fuel flow (X11). Full power metered fuel pressure is generally set between 16.0 and 17.0 psid (relative to turbo discharge pressure,P5). Corresponding metered fuel flows are 130 to 140 pph. During the trim at idle and full power, aneroid reference pressure (PREF) is set equal to trim full power turbo discharge pressure (approximately 43 to 44 inches of mercury). This pressure should be held constant for subsequent simulations for the same trim setting. Aneroid movement with changes in turbo discharge pressure is referenced to PREF, which may be regarded as a trim parameter.

After triming the simulation, subsequent simulations can be made varying altitude, engine speed, turbo discharge pressure, throttle angle, or any other input parameter desired to match a given operating condition.

Deck output consists of the results of the iteration process (X1 thru X11) after every 100 completed iteration loops, along with a parameter labeled "B". This parameter is the magnitude of the objective function as described in the discussion section of this report. The iteration continues until the value of the objective function is less than the value input of TOL (Card 2) or until the number of iterations exceeds NMAX. The values of X1 thru X11 corresponding to the sample output are given below, followed by a complete listing of the FORTRAN source program.

| Computer Output | Fuel System Parameter | Units | Idle Value | Full Power Value |
|---|---|---|---|---|
| X1 | P1,Pump Inlet Pressure | psia | 14.63 | 10.82 |
| X2 | P2,Pump Discharge Pressure | psia | 21.40 | 59.15 |
| X3 | P3, Absolute Metered Fuel Pressure | psia | 18.59 | 38.88 |
| X4 | P4, Nozzle Pressure | psia | 14.79 | 33.21 |
| X5 | P6, Variable Orifice Discharge Pressure | psia | 20.96 | 28.80 |
| X6 | P7, Vapor Separator Discharge Pressure | psia | 14.77 | 15.39 |
| X7 | Supply Line Flow Rate | pph | 26.20 | 199.6 |
| X8 | Pump Flow Rate | pph | 149.1 | 574.8 |
| X9 | Vapor Separator Flow Rate | pph | 19.05 | 58.77 |
| X10 | Variable Orifice Flow Rate | pph | 122.9 | 375.2 |
| X11 | Metered Fuel Flow Rate | pph | 7.14 | 140.8 |
| B | Remainder Term | - | 0.00094 | 0.0085 |
| N | Number of Iterations | - | 1891 | 2500 |

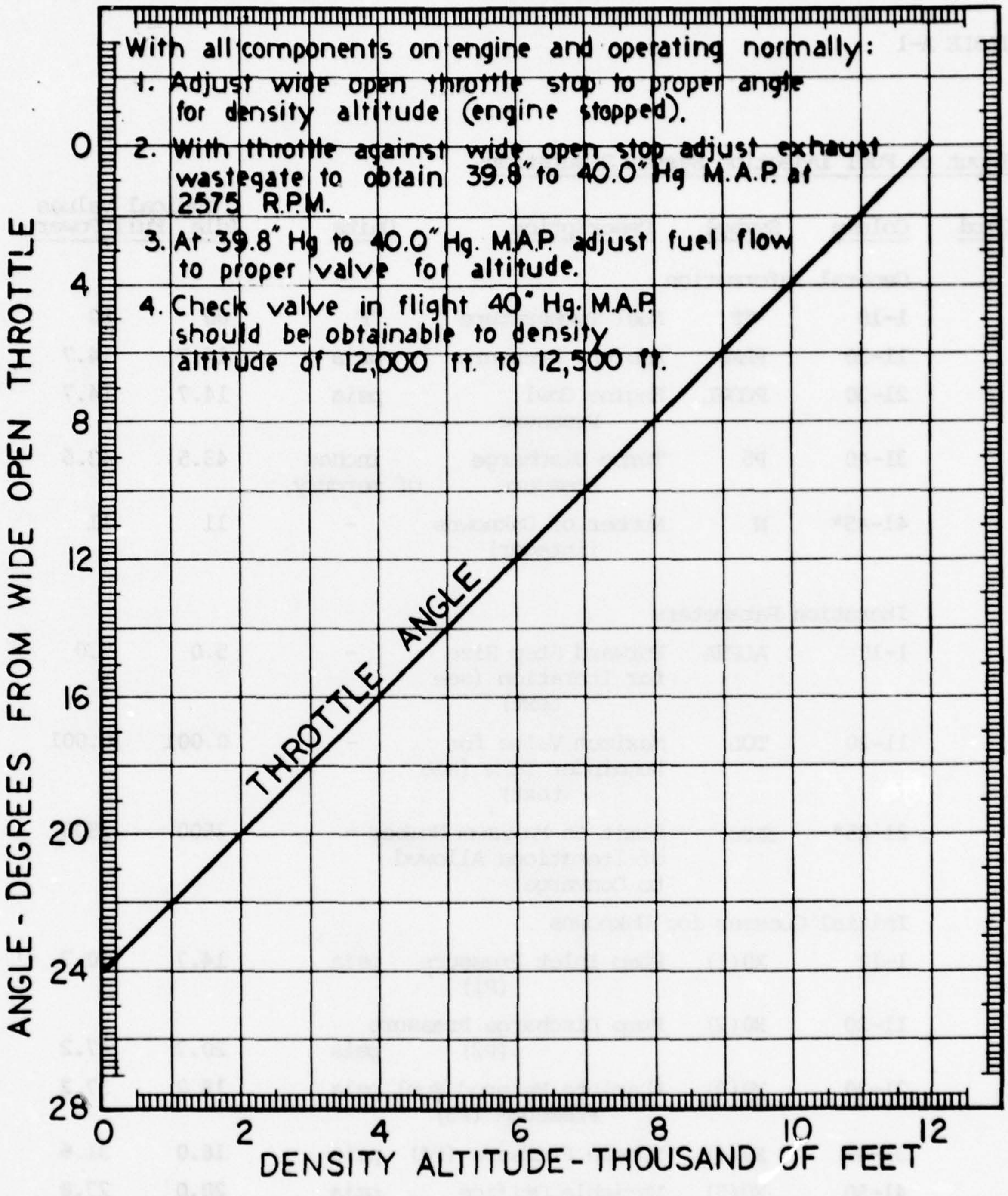


**FIGURE A-1. INSTRUCTIONS FOR ADJUSTMENT OF EXHAUST GAS WASTEGATE**

TABLE A-1

Input to Fuel Injection System Simulation

| Card | Column | Symbol | Description | Units | Typical Values Idle | Full Power |
|---|---|---|---|---|---|---|
| 1 | General Information | | | | | |
| | 1-10 | TF | Fuel Temperature | °F | 80 | 80 |
| | 11-20 | PAMB | Ambient Pressure | psia | 14.7 | 14.7 |
| | 21-30 | PCOWL | Engine Cowl Pressure | psia | 14.7 | 14.7 |
| | 31-40 | P5 | Turbo Discharge Pressure | inches of mercury | 43.5 | 43.5 |
| | 41-45* | N | Number of Unknowns (integer) | - | 11 | 11 |
| 2 | Iteration Parameters | | | | | |
| | 1-10 | ALPHA | Forward Step Size for Iteration (see text) | - | 5.0 | 5.0 |
| | 11-20 | TOL | Maximum Value for Remainder Term (see text) | - | 0.001 | 0.001 |
| | 21-25* | NMAX | Limit on Maximum Number of Iterations Allowed to Converge | - | 2500 | 2500 |
| 3 | Initial Guesses for Unknowns | | | | | |
| | 1-10 | X0(1) | Pump Inlet Pressure (P1) | psia | 14.7 | 10.7 |
| | 11-20 | X0(2) | Pump Discharge Pressure (P2) | psia | 20.7 | 47.2 |
| | 21-30 | X0(3) | Absolute Metered Fuel Pressure (P3) | psia | 18.2 | 37.2 |
| | 31-40 | X0(4) | Nozzle Pressure (P4) | psia | 16.0 | 31.6 |
| | 41-50 | X0(5) | Variable Orifice Discharge Pressure (P6) | psia | 20.0 | 27.8 |
| | 51-60 | X0(6) | Vapor Separator Discharge Pressure (P7) | psia | 14.7 | 14.7 |
| | 61-70 | X0(7) | Supply Line Flow Rate | pph | 23.0 | 181.0 |

* Integer Value. Input Right Adjusted in Input Field.

Table A-1 (cont'd)

| Card | Column | Symbol | Description | Units | Typical Values Idle | Typical Values Full Power |
|---|---|---|---|---|---|---|
| | 71-80 | XO(8) | Pump Flow Rate | pph | 150. | 617. |
| 4 | Initial Guesses for Unknowns (continued) | | | | | |
| | 1-10 | XO(9) | Vapor Separator Flow Rate | pph | 17.0 | 53.9 |
| | 11-20 | XO(10) | Variable Orifice Flow Rate | pph | 127. | 436. |
| | 21-30 | XO(11) | Metered Fuel Flow Rate | pph | 6.0 | 127. |
| 5 | Supply Line Data | | | | | |
| | 1-10 | XK | Line K-Factor (Ref3) | - | 4.45 | 4.45 |
| | 11-20 | DP | Line Diameter | Inch | 0.20 | 0.20 |
| | 21-30 | XL | Line Length | Inch | 180. | 180. |
| | 31-40 | EPSP | Line Surface Roughness (Ref 3) | Inch | 0.000125 | 0.000125 |
| | 41-50 | ZO | Line Elevation at Fuel Tank Relative to an Arbitrary Datum | Inch | 0. | 0. |
| | 51-60 | Z1 | Line Elevation at Pump Inlet Relative to Same Datum | Inch | 0. | 0. |
| 6 | Fuel Pump Data | | | | | |
| | 1-10 | RPM | Pump Speed (Equals Engine Speed for TSIO-360-E) | rpm | 700 | 2575 |
| | 11-20 | DISP | Pump Displacement | cu.inch | 0.226 | 0.226 |
| | 21-30 | EFF | Pump Efficiency | - | 0.9371 | 0.9371 |
| 7 | Variable Orifice Data | | | | | |
| | 1-10 | ADJVO | Variable Orifice Adjustment | inch | 0.145 | 0.145 |
| | 11-20 | PREF | Aneroid Reference Pressure | inches mercury | 43.5 | 43.5 |
| | 21-30 | AMS | Slope of Aneroid Movement with Pressure | in/inch mercury | .00925 | .00925 |

Table A-1 (Cont'd)

| Card | Column | Symbol | Description | Units | Typical Values Idle | Typical Values Full Power |
|---|---|---|---|---|---|---|
| | 31-40 | EROR | Allowable Error in Variable Orifice Iteration Loop. Maximum position error | in | 0.01 | 0.01 |
| 8 | Relief Valve Data | | | | | |
| | 1-10 | XK | Idle Relief Valve Spring Constant | lb/in inch | 13.7 | 13.7 |
| | 11-20 | RD | Pressure Disk Effective Radius | inch | 0.326 | 0.326 |
| | 21-30 | SAL | Idle Relief Valve Spring Length Adjustment | inch | 0.362 | 0.362 |
| 9 | Throttle Data | | | | | |
| | 1-10 | ALFA | Throttle Angle From Full Open Throttle | degrees | 72.0 | 24.0 |
| | 11-20 | ADJCU | Idle Fuel Flow Adjustment | degrees | 5.0 | 5.0 |
| 10 | Manifold Valve Data | | | | | |
| | 1-10 | SALM | Manifold Valve Spring Adjustment (set at factory) | inch | 0.2452 | 0.2452 |
| 11 | Vapor Return Line Data | | | | | |
| | 1-10 | XKR | Line K-Factor (Ref3) | - | 16.4 | 16.4 |
| | 11-21 | DR | Line Daimeter | inch | 0.20 | 0.20 |
| | 21-30 | XLR | Line Length | inch | 180. | 180. |
| | 31-40 | EPSR | Line Surface Roughness (Ref 3) | inch | 0.000125 | 0.000125 |

Computer Program listing is attached.

```
0001          DIMENSION MS(30,2),D(30),D1(30),EPS(30,30),EPS1(30,30),XI(30),
             C XOI(30),E(30),XO(30),DENS(50),VIS(50)
0002          COMMON RHO,VISC,PI,PAMB,PCCWL,P5
0003          COMMON/AAA/ M1
0004          COMMON/THREE/ XKF,DP,XL,ZO,Z1,EPSP
0005          COMMON/FOUR/  DISP,EFF,RPM
0006          COMMON/FIVE/ ADJVO,PREF,AMS,ERUK,AMKF,AMOP,NMAX
0007          COMMON/SIX/   XK,RD,SAL
0008          COMMON/EIGHT/ ALFA,ADJCU
0009          COMMON/XNINE/ SALM
0010          COMMON/ELEVN/ XKR,DR,XLR,ZOR,Z1R,EPSR
0011          DATA DENS / 1.,1.,5.,0.,-20.,20.,60.,100.,140.,6.47,6.31,6.15,
             C 5.99,5.83 /
0012          DATA VIS / 1.,1.,16.,0.,-20.,0.,10.,20.,30.,40.,50.,60.,70.,80.,
             C 90.,100.,110.,120.,130.,140.,1.15,0.95,0.89,0.84,0.78,0.74,0.70,
             C 0.67,0.63,0.60,0.58,0.55,0.52,0.50,0.49,0.48 /
0013          PI=3.14159
0014          BP=0.0
0015          WRITE(3,20)
0016          WRITE(3,15)
0017       15 FORMAT(/ 20X,'**** GENERAL INPUT DATA ****',///)
0018          READ(1,10) TF,PAMB,PCCWL,P5,N
0019       10 FORMAT(4F10.5,I5)
0020          READ(1,40) ALPHA,TOL,NMAX
0021       40 FORMAT(2F10.5,I5)
0022          WRITE(3,21) ALPHA
0023       21 FORMAT(1H1,' FORWARD STEP SIZE FOR ITERATION IS ',F10.4)
0024          WRITE(3,41) TOL,NMAX
0025       41 FORMAT(/,' ITERATION TOLERANCE FOR THIS RUN IS ',F10.5,/,
             C ' MAX NUMBER OF ITERATIONS IS ',I5)
0026          BETA=ALPHA/10.
0027          READ(1,11) (XO(I),I=1,N)
            C THESE ARE THE INITIAL GUESSES FOR THE UNKNOWNS
0028       11 FORMAT(8F10.5)
0029          CALL ENGUNB(DENS,1,TF,C.,RHO,11)
0030          CALL ENGUNB(VIS,1,TF,0.,VISC,12)
0031          RHO=RHO*7.481
0032          VISC=VISC*1.076E-05*RHC
0033          WRITE(3,12)
0034       12 FORMAT( / 3X,'FUEL TEMP',10X,'AMB PRESS',10X,'COWL PRESS',10X,
             C 'T/C DISCH PRESS',10X,'FUEL DENSITY',10X,'FUEL VISC',/)
0035          WRITE(3,13)
0036       13 FORMAT(5X,'DEG F',14X,'PSIA',15X,'PSIA',15X,'IN. HG. ABS.',13X,
             C 'LBM/CU FT',13X,'LBM/(FT*SEC)',/)
0037          WRITE(3,14) TF,PAMB,PCCWL,P5,RHO,VISC
0038       14 FORMAT(5X,F5.1,14X,F5.2,14X,F5.2,18X,F5.2,18X,F5.2,16X,1PE9.3,//)
0039          READ(1,11) XK,DP,XL,EPSP,ZO,Z1
0040          WRITE(3,16)
0041       16 FORMAT(/,20X,'**** INLET LINE INPUT DATA ****',//)
0042          WRITE(3,17) XK,DP,XL,ZC,Z1,EPSP
0043       17 FORMAT(3X,'LINE K-FACTOR = ',F10.5,3X,'LINE DIA = ',F10.2,2X,'IN',
             C3X,'LINE LENGTH = ',F10.2,2X,'IN',3X,'TANK FLUID LEVEL = ',F10.2,
             C2X,'IN',/,' PUMP LEVEL = ',F10.2,2X,'IN',3X,'SURF ROUGH =',E11.4)
0044          READ(1,11) RPM,DISP,EFF
```

```
0045          WRITE(3,18)
0046       18 FORMAT(/,20X,'**** PUMP INPUT DATA ****',//)
0047          WRITE(3,19) RPM,DISP,EFF
0048       19 FORMAT(3X,'PUMP SPEED = ',F10.1,3X,'PUMP DISP = ',F10.4,2X,'CU IN'
             C,3X,'PUMP VOLUMETRIC EFFICIENCY = ',F10.3)
0049          READ(1,11) ADJVO,PREF,AMS,EROR
0050          WRITE(3,30)
0051       30 FORMAT(/,20X,'**** VARIABLE ORIFICE INPUT DATA ****',//)
0052          WRITE(3,31) ADJVO,PREF,AMS,EROR
0053       31 FORMAT(3X,'ADJUSTMENT=',F10.4,2X,'IN',3X,'REF PRESS=',F10.2,2X,
             C 'IN HG ABS',3X,'ANEROID SLOPE = ',F10.5,2X,'IN/IN HG',
             C3X,'ERROR= ',F10.5)
0054          READ(1,11) XK,RD,SAL
0055          WRITE(3,32)
0056       32 FORMAT(/,20X,'**** IDLE RELIEF VALVE INPUT DATA ****',//)
0057          WRITE(3,33) XK,RD,SAL
0058       33 FORMAT(3X,'VALVE SPRING CONSTANT =',F10.2,2X,'LB-F/IN',3X,'PRESS D
             CISK EFFECTIVE RADIUS = ',F10.3,3X,'SPRING ADJUSTED LENGTH = ',
             C F10.3,2X,'IN')
0059          READ(1,11) ALFA,ADJCU
0060          WRITE(3,34)
0061       34 FORMAT(/,20X,'**** CONTROL UNIT INPUT DATA ****',//)
0062          WRITE(3,35) ALFA,ADJCU
0063       35 FORMAT(3X,'THROTTLE ANGLE =',F10.1,2X,'DEG',3X,'IDLE ADJUSTMENT ='
             C ,F10.1)
        C  ALFA IS ANGLE FROM FULL THROTTLE (DEG)
        C  ADJ  IS IDLE ADJUSTMENT FROM MIN FLOW (DEG)  MIN IS 0,MAX IS +10 .
0064          IF(ADJCU .LT.0.) ADJCU=0.0
0065          IF(ADJCU .GT. 10.) ADJCU=10.
0066          ALFA=ALFA + 15. - ADJCU
0067          ALFA=ALFA/57.295787
0068          READ(1,11) SALM
0069          WRITE(3,36)
0070       36 FORMAT(/,20X,'**** MANIFOLD VALVE INPUT DATA ****',//)
0071          WRITE(3,37) SALM
0072       37 FORMAT(3X,'ADJUSTED SPRING LENGTH = ',F10.4,2X,'IN')
0073          ZOR=ZO
0074          Z1R=Z1
0075          READ(1,11) XKR,DR,XLR,EPSR
0076          WRITE(3,38)
0077       38 FORMAT(/,20X,'**** RETURN LINE INPUT DATA ****',//)
0078          WRITE(3,39) XKR,DR,XLR,EPSR
0079       39 FORMAT(3X,'LINE K-FACTOR = ',F10.5,3X,'LINE DIA = ',F10.2,2X,'IN',
             C 3X,'LINE LENGTH = ',F10.2,2X,'IN',3X,'SURF ROUGH =',E11.4)
        C THE BEGINNING OF ROSENBROCK'S ALGORITHM
        C ALPHA=FACTOR BY WHICH LENGTH OF STEP SIZE IS INCREASED.
        C BETA=FACTOR BY WHICH LENGTH OF STEP SIZE IS DECREASED.
        C E(I)=MAGNITUDE OF INITIAL STEP SIZE.
        C THE USER SELECTS VALUES FOR ALPHA AND BETA WHICH LEAD TO RAPID
        C CONVERGENCE. TRIAL AND ERROR WITH TWO OR THREE ITERATIONS IS
        C USUALLY SUFFICIENT
0080          WRITE(3,20)
0081       20 FORMAT(1H1)
0082          DO 100 NC=1,N
```

```
  100 E(NC)=5.
      DO 101 NC=1,N
      XOI(NC)=XO(NC)
      XI(NC)=XO(NC)
  101 DI(NC)=0.
      DO 119 NC=1,N
      DO 120 NK=1,N
  120 EPS(NC,NK)=0.0
  119 CONTINUE
      M1=0
      DO 125 NC=1,N
      MS(NC,1)=0
  125 MS(NC,2)=0
      B=F(XO)
      NS=0
      DO 102 NC=1,N
  102 EPS(NC,NC)=1.
      WRITE(3,29)
   29 FORMAT(14H    I         XO)
      WRITE(3,26) (I,XO(I),I=1,N)
   26 FORMAT(I5,1PE17.6)
      WRITE(3,23) B
   23 FORMAT(4H B= ,E15.6)
      DO 103 NC=1,N
  103 D(NC)=E(NC)
  104 CONTINUE
      DO 105 II=1,2000
      IF (NS .GE. 1) GO TO 1C6
      KK=II-1
      I= MOD(KK,N)+1
      M1=M1+1
      IF(M1 .GE. NMAX) GO TO 200
      DO 107 NC=1,N
  107 XO(NC)=D(I) *EPS(NC,I) + XI(NC)
      W1=F(XO)
      IF(W1.LT.B) GO TO 108
      B=W1
      DO 109 NC=1,N
  109 XI(NC)=XO(NC)
      D1(I)=D1(I)+D(I)
      D(I)=ALPHA*D(I)
      MS(I,1)=MS(I,1)+1
      GO TO 110
  108 D(I)=-BETA*D(I)
      MS(I,2)=MS(I,2)+1
  110 NS=10
      DO 111 L=1,N
      N2=MS(L,1)*MS(L,2)
  111 NS=MINO(NS,N2)
  105 CONTINUE
  106 CONTINUE
C GET FILE(IN) NEW DIRECTIONS
      DO 112 NC=1,N
      DO 113 NK=1,N
```

```
 0136        113 EPS1(NC,NK)=0.0                                                        000162
 0137        112 CONTINUE                                                               000163
 0138            DO 114 NC=1,N                                                          000164
 0139        114 EPS1(NC,N)=D1(N)*EPS(NC,N)                                             000165
 0140            NI=N-1                                                                 000166
 0141        123 IF(NI.LT.1) GO TO 124                                                  000167
 0142            DO 116 NC=1,N                                                          000168
 0143        116 EPS1(NC,NI)=D1(NI)*EPS(NC,NI)+EPS1(NC,NI+1)                            000169
 0144            NI=NI-1                                                                000170
 0145            GO TO 123                                                              000171
 0146        124 CONTINUE                                                               000172
 0147            DO 300 I=1,N                                                           000173
 0148            DO 301 NC=1,N                                                          000174
 0149        301 EPS(NC,I)=EPS1(NC,I)                                                   000175
 0150            JJ=I-1                                                                 000176
 0151            DO 400 J=1,JJ                                                          000177
 0152            RR1=0.                                                                 000178
 0153            DO 401 NC=1,N                                                          000179
 0154            EPS1P=EPS1(NC,I)*EPS(NC,J)                                             000180
 0155        401 RR1=RR1+EPS1P                                                          000181
 0156            DO 402 NC=1,N                                                          000182
 0157        402 EPS(NC,I)=EPS(NC,I)-RR1*EPS(NC,J)                                      000183
 0158        400 CONTINUE                                                               000184
 0159            RR=0.                                                                  000185
 0160            DO 302 NC=1,N                                                          000186
 0161            ESP1P=EPS(NC,I)*EPS(NC,I)                                              000187
 0162        302 RR=RR+ESP1P                                                            000188
 0163            RR=SQRT(RR)                                                            000189
 0164            DO 303 NC=1,N                                                          000190
 0165        303 EPS(NC,I)=EPS(NC,I)/RR                                                 000191
 0166        300 CONTINUE                                                               000192
 0167            DO 117 NC=1,N                                                          000193
 0168            XOI(NC)=XI(NC)                                                         000194
 0169        117 D1(NC)=0.                                                              000195
 0170            DO 118 NC=1,N                                                          000196
 0171            MS(NC,1)=0                                                             000197
 0172        118 MS(NC,2)=0                                                             000198
 0173            NS=0                                                                   000199
           C THE FOLLOWING STATEMENT IS AN ERROR CRITERION THAT CAN BE USER             000200
           C ADJUSTED. B IS THE LATEST VALUE OF THE OBJECTIVE FUNCTION AND              000201
           C THIS VALUE MUST BE LOWER THAN SOME SPECIFIED CONSTANT                      000202
           C (TOL) BEFORE THE SEARCH PROCEDURE STOPS                                    000203
 0174            IF(ABS(B) .LT. TOL) GO TO 200                                          000204
           C M1 IS THE NUMBER OF FUNCTION EVALUATIONS THAT HAVE OCCURRED DURING         000205
           C THE SEARCH FOR THE MINIMUM VALUE OF THE OBJECTIVE FUNCTION. IF M1          000206
           C BECOMES TOO LARGE (GE NMAX), THE SEARCH PROCEDURE STOPS                    000207
 0175            IF(M1 .GE. NMAX) GO TO 200                                             000208
 0176            KJ=MOD(M1,100)                                                         000209
 0177            IF(KJ .NE. 0) GO TO 104                                                000210
 0178            IF(BP .EQ. 0) GO TO 104                                                000211
 0179            RED=ABS((BP-B)/BP)                                                     000212
 0180            IF(RED.LT. .05) GO TO 200                                              000213
 0181            BP=B                                                                   000214
 0182            GO TO 104                                                              000215
```

```
DOS FORTRAN IV 360N-FO-479 3-8          MAINPGM          DATE   01/09/78       TIME     13.24.12          PAGE 0005

                C THIS IS THE MAIN ITERATION LOOP RETURN PATH                                        000216
                C ROSENBROCH'S ALGORITHM ENDS HERE                                                   000217
 0183             200 WRITE(3,25) M1                                                                 000218
 0184              25 FORMAT(37H NUMBER OF ITERATIONS REQUIRED EQUALS,I5)                            000219
 0185                 WRITE(3,28)                                                                    000220
 0186              28 FORMAT(14H      I         XI)                                                  000221
 0187                 WRITE(3,26) (I,XI(I),I=1,N)                                                    000222
 0188                 WRITE(3,27) B                                                                  000223
 0189              27 FORMAT(5H  B= ,E15.6)                                                          000224
 0190                 WRITE(3,42) AMRF,AMDP                                                          000225
 0191              42 FORMAT(/,' ANEROID MOVEMENT DUE TO ROD FORCE EQUALS ',F10.5,                   000226
                  C/,' ANEROID MOVEMENT DUE TO T/C DISCHARGE PRESSURE EQUALS ',                      000227
                  C F10.5)                                                                           000228
 0192                 CALL EXIT                                                                      000229
 0193                 END                                                                            000230
```

```
           C    THE FOLLOWING FUNCTION PROCEDURE DEFINES THE OBJECTIVE FUNCTION.
           C    EQUATION 15 FROM HUEBNER'S TEXT
0001              FUNCTION F(X)
0002              DIMENSION X(30)
0003              COMMON/AAA/ M1
0004              T=F1(X(7),X(9),X(11))**2 + F2(X(7),X(8),X(10))**2
                C + F3(X(1),X(7))**2 + F4(X(1),X(2),X(8))**2
                C + F5(X(2),X(5),X(10))**2 + F6(X(1),X(5))**2
                C + F7(X(2),X(6),X(9))**2 + F8(X(2),X(3),X(11))**2
                C + F9(X(3),X(4),X(11))**2 + F10(X(4),X(11))**2
                C + F11(X(6),X(9))**2
0005              F=-T
0006              J=MOD(M1,100)
0007              IF(J.NE.0) GO TO 513
0008              WRITE(3,512) F,M1
0009          512 FORMAT(9H F EQUALS,F17.6,10H M1 EQUALS,I5)
0010              WRITE(3,28)
0011           28 FORMAT(14H    I         XI)
0012              WRITE(3,26) (I,X(I),I=1,11)
0013           26 FORMAT(I5,1PE17.6)
0014          513 CONTINUE
0015              RETURN
0016              END
```

```
C LISTING OF FUNCTION PROCEDURES FOR THE NETWORK. EACH FUNCTION
C REPRESENTS EITHER THE PRESSURE-FLOW RELATION FOR A FLOW PATH OR
C AN EXPRESSION OF FLOW CONTINUITY AT SOME NODES.
C FOR THE LTSIO-360E FUEL INJECTION SIMULATION I DEFINED
C       X(1)=P1
C       X(2)=P2
C       X(3)=P3
C       X(4)=P4
C       X(5)=P6
C       X(6)=P7
C       X(7)=WA
C       X(8)=WB
C       X(9)=WC
C       X(10)=WD
C       X(11)=WF
      FUNCTION F1(X7,X9,X11)
C       CONTINUITY AT JUNCTION 0
      COMMON/AAA/ M1
      F1= X7-X11-X9
      JJJ=MOD(M1,100)
      IF(JJJ.NE.0) GO TO 1000
      WRITE(3,1100) F1
 1100 FORMAT(  E13.4)
 1000 CONTINUE
      RETURN
      END
```

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DOS FORTRAN IV 360N-FO-479 3-8          F2                    DATE   01/09/78      TIME     13.25.15       PAGE 0001

0001               FUNCTION F2(X7,X8,X10)                                                      000280
             C       CONTINUITY AT JUNCTION 1                                                  000281
0002               COMMON/AAA/ M1                                                              000282
0003               F2= X8-X7-X10                                                               000283
0004               JJJ=MOD(M1,100)                                                             000284
0005               IF(JJJ.NE.0) GO TO 1000                                                     000285
0006               WRITE(3,1100) F2                                                            000286
0007          1100 FORMAT(  E13.4)                                                             000287
0008          1000 CONTINUE                                                                    000288
0009               RETURN                                                                      000289
0010               END                                                                         000290
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```
0001          FUNCTION F3(X1,X7)
        C       PRESSURE LOSS THROUGH THE SUPPLY LINE
0002          DIMENSION FRI1(217),FRI2( 56),FRIC(273)
0003          COMMON RHO,VISC,PI,PAMB,PCCWL,P5
0004          COMMON/AAA/ M1
0005          COMMON/THREE/XKO,D,XL,ZO,Z1,EPS
0006          EQUIVALENCE (FRIC(1),FRI1(1)),(FRIC(218),FRI2(1))
0007          DATA FRI1 / 1.,1.,17.,14.,1.E-06,1.E-05,5.E-05,1.E-04,2.E-04,
             C4.E-04,6.E-04,8.E-04,1.E-03,2.E-03,4.E-03,6.E-03,8.E-03,1.E-02,
             C1.5E-02,2.E-02,3.E-02,3.E+03,5.E+03,8.E+03,1.5E+04,3.E+04,6.E+04,
             C1.E+05,2.E+05,4.E+05,8.E+05,2.E+06,4.E+06,8.E+06,1.E+07,.044,.037,
             C.032,.0275,.023,.0198,.0178,.0155,.0136,.012,.0102,.0092,.0083,
             C.0081,.044,.037,.032,.0275,.023,.0198,.0178,.0155,.0138,.0122,
             C.0108,.0098,.0092,.0085,.044,.037,.032,.0275,.023,.0198,.018,.016,
             C.0142,.013,.0118,.0112,.0105,.0108,.044,.037,.032,.0275,.023,
             C.0202,.0184,.0164,.0145,.0137,.0128,.0122,.0120,.0120,.044,.037,
             C.032,.0275,.024,.0208,.0190,.0170,.0158,.0149,.0141,.0139,.0138,
             C.0138,.044,.037,.032,.0275,.0245,.0217,.020,.0182,.0172,.0167,
             C.016,.016,.016,.016,.044,.037,.032,.0275,.025,.0222,.0208,.0192,
             C.0183,.0180,.0175,.0175,.0175,.0175,.044,.0375,.033,.029,.0252,
             C.023,.0215,.0202,.0195,.019,.0189,.0188,.0188,.0188,.044,.038,
             C.034,.0295,.0258,.0235,.0222,.021,.0202,.02 ,.02,.02,.02,.02,.045,
             C.039,.0355,.031,.028,.026,.025,.0242,.024,.0237,.0237,.0237,.0237,
             C.0237,.047,.0415,.038,.034,.0315,.03,.0295,.029,.029,.029,.029,
             C.029,.029,.029,.0485,.0435,.04,.0365,.0348,.0335,.033,.0325,.032,
             C.032,.032,.032,.032,.032,.0495,.045,.042,.0395,.0375,.036,.0358,
             C.0355,.0355,.0355,.0355,.0355,.0355,.0355 /
0008          DATA FRI2 / .052,.047,.044,.0415,.040,.039,.0382,.038,.038,.038,
             C.038,.038,.038,.038,.055,.0515,.049,.0462,.045,.044,.044,.044,
             C.044,.044,.044,.044,.044,.044,.059,.0555,.053,.051,.050,.049,.049,
             C.049,.049,.049,.049,.049,.049,.049,.065,.063,.061,.059,.058,.0575,
             C.0575,.0575,.0575,.0575,.0575,.0575,.0575,.0575 /
        C   FLOW IN PPH,DIA IN INCHES,ABS. VIS IN LBM/(FT*SEC),EPS IN INCHES
0009          W=X7
0010          A=PI*(D**2)/4.
0011          REY=(W*D/(A*VISC))*(12./3600.)
0012          REY=ABS(REY)
0013          EOD=EPS/D
0014          CALL ENGUNB(FRIC,1,EOD,REY,FF,IE)
0015          IF(REY.LT.3000) FF =64./(REY+.001)
0016          Q=0.5*W*ABS(W)*144./(3600.)**2/RHO/(A**2)/32.2
0017          XK=XKO+FF*XL/D
0018          DP=XK*Q
0019          DP=DP+ RHO*(Z1-ZO)/1728.
0020          F3= PAMB-X1-DP
0021          JJJ=MOD(M1,100)
0022          IF(JJJ.NE.0) GO TO 1000
0023          WRITE(3,1100) REY,FF,Q,DP,F3
0024     1100 FORMAT( 5E13.4)
0025     1000 CONTINUE
0026          RETURN
0027          END
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DOS FORTRAN IV 360N-FO-479 3-8          F4                 DATE    01/09/78      TIME     13.25.46        PAGE 0001

0001         FUNCTION F4(X1,X2,X8)                                                        000343
        C     PRESSURE RISE THROUGH VANE PUMP                                             000344
        C    EFFICIENCY BASED ON RHO OF 45.41                                             000345
0002         COMMON RHO,VISC,PI,PAMB,PCCWL,PS                                             000346
0003         COMMON/AAA/ M1                                                               000347
0004         COMMON/FOUR/  DISP,EFF,RPM                                                   000348
0005         DIMENSION PUMP(100)                                                          000349
0006         DATA PUMP /1.,1.,17.,0.,0.,75.,111.,145.,175.,203.5,227.,249.,               000350
            C 268.,285.,302.,318.,334.,364.,394.,424.,454.,0.,5.,10.,15.,                 000351
            C 20.,25.,30.,35.,40.,45.,50.,55.,60.,70.,80.,90.,100./                       000352
0007         RHOT=45.41                                                                   000353
0008         W=X8                                                                         000354
        C   ACTUAL FLOW IS NOW CONVERTED TO MEASURED FLOW                                 000355
0009         W=W/1.02                                                                     000356
0010         WLEAK=(RHO*DISP/1728.*RPM*60.*EFF - W) *SQRT(RHOT/RHO)                       000357
0011         IF(WLEAK.LT.0.) WLEAK=0.                                                     000358
0012         CALL ENGUNB(PUMP,1,WLEAK,0.,DP,IE)                                           000359
0013         F4=(X2-X1)-DP                                                                000360
0014         JJJ=MOD(M1,100)                                                              000361
0015         IF(JJJ.NE.0) GO TO 1000                                                      000362
0016         WRITE(3,1100) WLEAK,DP,F4                                                    000363
0017    1100 FORMAT( 3E13.4)                                                              000364
0018    1000 CONTINUE                                                                     000365
0019         RETURN                                                                       000366
0020         END                                                                          000367
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DOS FORTRAN IV 360N-FO-479 3-8          F5                DATE    01/09/78      TIME     13.26.00          PAGE 0C01

0001               FUNCTION FS(X2,X5,X10)
          C         PRESSURE DROP THROUGH VARIABLE ORIFICE
0002               COMMON RHO,VISC,PI,PAMB,PCCWL,P5
0003               COMMON/AAA/ M1
0004               COMMON/FIVE/ ADJVO,PREF,AMS,EROR,AMRF,AMDP,NMAX
0005               DIMENSION AKFCT(100)
0006               DATA AKFCT / 1.,1.,16.,C.,C.,0.001,0.002,0.003,0.004,0.005,0.006,
                 C0.007,0.008,0.0087,0.CC9,0.010,0.012,0.014,0.016,0.018,0.70,0.83,
                 C0.93,1.01,1.08,1.13,1.175,1.205,1.22,1.22,1.24,1.36,1.60,1.85,2.11
                 C,2.39 /
          C    ANEROID SPRING CONSTANT
0007               XKA=27.5
          C    ORIFICE ROD DIAMETERS
0008               DO=0.249
          C  FLOW IN PPH,PRESS PSI ABS, ADJVO INCHES. RHO LB MASS/CU FT
          C      AMS IS SLOPE OF ANEROID DEFL DUE TO T/C PRESS DROP FROM REF VALVE
0009               WD=X10
0010               P2=X2
0011               AMDP=(PREF-P5)*AMS
0012               N=0
0013               AMRF=0.0
          C  INITIATION OF VALUES FOR AREA CALC
0014               DH=0.25
0015               FVOP=0.0
0016               DS=DO
0017               BETA=3.562
0018               BETAP=12.83
0019               XLTPR=0.180
0020               XLMX=0.240
0021               R3=0.0425
0022               BETA=BETA/57.295787
0023               BETAP=BETAP/57.295787
0024               R1=DS/2.
0025               DELTAS=(DH-DS)*0.50
0026               AH=PI*(DH**2)/4.
0027               DELTA=ADJVO+AMDP
0028             2 CONTINUE
0029               IF(DELTA.LT.0.0) DELTA=0.0
0030               IF(DELTA.LE.XLTPR) R2=R1-DELTA*TAN(BETA)
0031               IF(DELTA.GT.XLTPR) R2=R1-XLTPR*TAN(BETA)-(DELTA-XLTPR)*TAN(BETAP)
0032               IF(DELTA.GT.XLMX) GO TC 600
0033               AREA=AH-PI*(R2)**2
0034               GO TO 700
0035           600 R2=R1-XLTPR*TAN(BETA)-(XLMX-XLTPR)*TAN(BETAP)
0036               HL=DELTA-XLMX
0037               IF(R1.EQ.R2) HB=HL
0038               IF(R1.EQ.R2) GO TO 601
0039               HB=R1*(DELTA-XLMX)/(R1-R2)
0040           601 AREA=PI*R1*SQRT(R1**2+HB**2)-PI*R2*SQRT(R2**2+(HB-HL)**2)
                 C +PI*(R1+DELTAS)**2-PI*(R1)**2
0041               A2=PI*(R1)**2-PI*(R3)**2
0042               IF(A2.LT.AREA) AREA=A2
0043           700 ADRIF=AREA
0044               CALL ENGUNB(AKFCT,1,ADRIF,0.,AK,IE)
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      VEL=(WD/3600.)/(RHO*AORIF)*144.
      Q=0.5*RHO*(VEL**2)/(144.*32.2)
      FVO=Q*AK
      P6=P2-FVO
      IF(P6 .LT. 0.) P6=0.0
      R2MN=R1-XLTPR*TAN(BETA)-(XLMA-XLTPR)*TAN(BETAP)
      PAVG=(P2+P6)/2.
      D2=2.*R2MN
      RF=(P2-PAVG)*(PI/4.)*(DO**2-D2**2)+P6*(PI/4.)*(DO**2)
      AMRF=-RF/XKA
      IF(N.EQ. 0) GO TO 4
      IF(ABS(FVO-FVOP).GT. EROR) GO TO 4
C     IF PROGRAM PASSES THIS LAST TEST, ITERATION HAS CONVERGED
    6 F5=(X2-X5)-FVO
      JJJ=MOD(M1,100)
      IF(JJJ.NE.0) GO TO 1000
      WRITE(3,1100) AORIF,AK,Q,FVO,F5,DELTA
 1100 FORMAT( 6E13.4)
 1000 CONTINUE
      RETURN
    4 N=N+1
      FVOP=FVO
      IF( N .LE. 1000 ) GO TO 5
      WRITE(3,200) DOLD,DELTA,X2,X5,X10,AMRF,AORIF
  200 FORMAT( / 3X,' VARIABLE ORIFICE ITERATION FAILURE. DOLD= ',F10.5,
     C ' DELTA=  ',F10.5,/,5F10.5)
      M1=NMAX+1000
      GO TO 6
    5 IF(N.LT.3) GO TO 7
      DOLD=DELTA
      DO2=DOLD
      D2=ADJVO+AMDP+AMRF
      IF(DO2.EQ.DO1) GO TO 7
      XM=(D2-D1)/(DO2-DO1)
      B=D2-DO2*XM
      IF(XM.EQ.1.) GO TO 7
      DELTA=B/(1.-XM)
      DO1=DO2
      D1=D2
      GO TO 2
    7 DOLD=DELTA
      DO1=DELTA
      D1=ADJVO+AMDP+AMRF
    8 DELTA=(ADJVO+AMDP+AMRF+DOLD)/2.0
      GO TO 2
      END
```

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DOS FORTRAN IV 360N-FO-479 3-8          F6              DATE   01/09/78      TIME     13.26.19        PAGE 0001

 0001                FUNCTION F6(X1,X5)                                                    000468
               C      IDLE RELIEF VALVE PRESSURE DROP                                      000469
 0002                COMMON RHO,VISC,PI,PAMB,PCCAL,P5                                      000470
 0003                COMMON/AAA/ M1                                                        000471
 0004                COMMON /SIX/ XK,RD,SAL                                                000472
 0005                P1=X1                                                                 000473
 0006                R1=0.31                                                               000474
 0007                SFL=0.50                                                              000475
 0008                FRV=((SFL-SAL)*XK+(P5*14.696/29.92-P1)*PI*(RD**2))/(PI*(R1**2))       000476
 0009                F6=X5-X1-FRV                                                          000477
 0010                JJJ=MOD(M1,100)                                                       000478
 0011                IF(JJJ.NE.0) GO TO 1000                                               000479
 0012                WRITE(3,1100) FRV,F6                                                  000480
 0013           1100 FORMAT( 2E13.4)                                                       000481
 0014           1000 CONTINUE                                                              000482
 0015                RETURN                                                                000483
 0016                END                                                                   000484
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DOS FORTRAN IV 360N-FO-479 3-8          F7                DATE   01/09/78     TIME     13.26.33          PAGE 0001

0001              FUNCTION F7(X2,X6,X9)                                                    000485
            C       PRESSURE DROP ACROSS VAPOR SEPARATOR                                   000486
0002              COMMON RHO,VISC,PI,PAMB,PCCWL,P5                                         000487
0003              COMMON/AAA/ M1                                                           000488
0004              DIMENSION FLO(100)                                                       000489
0005              DATA FLO /1.,1.,16.,0.,0.,10.,20.,30.,35.,40.,45.,47.5,50.,              000490
                C 52.5,55.,57.5,60.,62.5,65.,75.,0.,3.5,7.1,11.,13.3,16.,19.7,             000491
                C 22.5,26.8,31.8,37.5,43.4,50.,57.,63.,89./                                000492
0006              W=X9                                                                     000493
            C  CONVERT TO MEASURED FLOW                                                    000494
0007              W=W/1.02                                                                 000495
0008              CALL ENGUNB(FLO,1,W,C.,DP,IE)                                            000496
0009              RHOT=45.48                                                               000497
0010              DP=DP*RHOT/RHO                                                           000498
0011              F7=(X2-X6)- DP                                                           000499
0012              JJJ=MOD(M1,100)                                                          000500
0013              IF(JJJ.NE.0) GO TO 1000                                                  000501
0014              WRITE(3,1100) DP,F7                                                      000502
0015         1100 FORMAT( 2E13.4)                                                          000503
0016         1000 CONTINUE                                                                 000504
0017              RETURN                                                                   000505
0018              END                                                                      000506
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DOS FORTRAN IV 360N-FO-479 3-8          F8                 DATE   01/09/78      TIME     13.26.47         PAGE 0001

0001              FUNCTION F8(XX2,XX3,X11)                                                         000507
            C      PRESSURE DROP ACROSS CONTROL UNIT                                               000508
0002              COMMON RHO,VISC,PI,PAMB,PCCNL,P5                                                 000509
0003              COMMON/AAA/ M1                                                                   000510
0004              COMMON /EIGHT/ ALFA,ADJ                                                          000511
0005              DIMENSION THROT( 50)                                                             000512
0006              DATA THROT / 1.,1.,17.,0.,0.,0.5,0.7,0.9,1.1,1.3,1.5,1.7,1.9,2.1,                000513
                 C2.3,2.5,2.7,2.9,3.1,3.3,3.5,.1,0.489,0.566,0.631,0.683,0.722,                    000514
                 C0.748,0.769,0.790,0.812,0.832,0.854,0.876,0.903,0.941,1.0,1.0 /                  000515
0007              RB=0.036                                                                         000516
0008              RC=0.44475                                                                       000517
0009              D=0.09375                                                                        000518
0010              H=0.406                                                                          000519
0011              XKFCT=1.50                                                                       000520
0012              W=X11                                                                            000521
0013              XBAR=RB*SIN(ALFA)                                                                000522
0014              YBAR=-RB*COS(ALFA)                                                               000523
0015              A=4.*((H-YBAR)**2+XBAR**2)                                                       000524
0016              B=4.*(H-YBAR)*(XBAR**2-RC**2+(D/2.)**2+YBAR**2-H**2)                             000525
0017              B=B-8.*H*XBAR**2                                                                 000526
0018              C=(XBAR**2-RC**2+(D/2.)**2+YBAR**2-H**2)**2                                      000527
0019              C=C+4.*XBAR**2*H**2-D**2*XBAR**2                                                 000528
0020              Y1=(-B-SQRT(B**2-4.*A*C))/(2.*A)                                                 000529
0021              Y2=(-B+SQRT(B**2-4.*A*C))/(2.*A)                                                 000530
0022              X1=-SQRT((D/2.)**2-(Y1-H)**2)                                                    000531
0023              X2=+SQRT((D/2.)**2-(Y2-H)**2)                                                    000532
0024              A=(H-YBAR)*(X2-X1)                                                               000533
0025              A=A+0.5*(X2*SQRT((D/2.)**2-X2**2)+(D/2.)**2*ARSIN(2.*X2/D))                      000534
0026              A=A-0.5*(X1*SQRT((D/2.)**2-X1**2)+(D/2.)**2*ARSIN(2.*X1/D))                      000535
0027              A=A-0.5*(X2*SQRT(RC**2-X2**2)+RC**2*ARSIN(X2/RC))                                000536
0028              A=A+0.5*(X1*SQRT(RC**2-X1**2)+RC**2*ARSIN(X1/RC))                                000537
0029              AEN=1000.*A                                                                      000538
0030              CALL ENGUNB(THROT,1,AEN,0.,CD,IE)                                                000539
0031              VEL=(W/RHO/A)*(144./3600.)/CD                                                    000540
0032              Q=(0.5*RHO*VEL*ABS(VEL))/(32.2*144.)                                             000541
0033              DP=XKFCT*Q                                                                       000542
0034              F8=(XX2-XX3)-DP                                                                  000543
0035              JJJ=MOD(M1,100)                                                                  000544
0036              IF(JJJ.NE.0) GO TO 1000                                                          000545
0037              WRITE(3,1100) A,CD,Q,DP,F8                                                       000546
0038         1100 FORMAT( 5E13.4)                                                                  000547
0039         1000 CONTINUE                                                                         000548
0040              RETURN                                                                           000549
0041              END                                                                              000550
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DOS FORTRAN IV 360N-FO-479 3-8          F9                 DATE   01/09/78        TIME      13.27.04        PAGE 0001

   0001             FUNCTION F9(X3,X4,X11)                                                   000551
              C       MANIFOLD VALVE PRESSURE DRCP                                           000552
   0002             COMMON RHO,VISC,PI,PAMB,PCCWL,P5                                         000553
   0003             COMMON/AAA/ M1                                                           000554
   0004             COMMON/XNINE/ XLADJ                                                      000555
   0005             DIMENSION ZANIF(100)                                                     000556
   0006             DATA ZANIF /1.,1.,4.,0.,0.,80.,160.,200.,0.,1.2,2.3,2.88/                000557
   0007             XK=0.2070                                                                000558
   0008             XLF=0.70                                                                 000559
   0009             RV=0.090                                                                 000560
   0010             DPC= XK*(XLF-XLADJ)/(PI*(RV**2))                                         000561
   0011             W=X11                                                                    000562
   0012             W=W/1.02                                                                 000563
   0013             CALL ENGUNB(ZANIF,1,W,0.,DP,IE)                                          000564
   0014             RHOT=45.41                                                               000565
   0015             DP=DP*RHOT/RHO                                                           000566
   0016             DP=DP+DPC                                                                000567
   0017             F9=(X3-X4)-DP                                                            000568
   0018             JJJ=MOD(M1,100)                                                          000569
   0019             IF(JJJ.NE.0) GO TO 1000                                                  000570
   0020             WRITE(3,1100) DP,F9                                                      000571
   0021        1100 FORMAT( 2E13.4)                                                          000572
   0022        1000 CONTINUE                                                                 000573
   0023             RETURN                                                                   000574
   0024             END                                                                      000575
```

```
0001            FUNCTION F10(X4,X11)
          C     NOZZLE PRESSURE DROP
0002            COMMON RHO,VISC,PI,PAMB,PCCNL,P5
0003            COMMON/AAA/ M1
0004            DIMENSION ZOZZ(100)
0005            DATA ZOZZ / 1.,1.,18.,C.,0.,10.,20.,30.,40.,50.,60.,70.,
              C 80.,90.,100.,110.,120.,130.,140.,150.,160.,200.,0.,0.15,0.30,
              C 0.551,1.05,1.65,2.4,3.3,4.35,5.50,6.6,7.95,9.30,10.7,12.15,
              C 13.6,15.2,23.75 /
0006            RHOT=45.41
0007            W=X11
0008            W=W/1.02
0009            CALL ENGUNB(ZOZZ,1,W,0.,DP,IE)
0010            DP=DP*RHOT/RHO
0011            F10=X4-P5*14.696/29.92-DP
0012            JJJ=MOD(M1,100)
0013            IF(JJJ.NE.0) GO TO 1000
0014            WRITE(3,1100) DP,F1C
0015       1100 FORMAT( 2E13.4)
0016       1000 CONTINUE
0017            RETURN
0018            END
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DOS FORTRAN IV 360N-FO-479 3-8          F11                 DATE   01/09/78     TIME    13.27.33        PAGE 0001

0001            FUNCTION F11(X6,X9)                                                  000598
        C        VAPOR RETURN LINE PRESSURE DROP                                     000599
0002            DIMENSION FRI1(217),FRI2( 56),FRIC(273)                              000600
0003            COMMON RHO,VISC,PI,PAMB,PCCWL,PS                                     000601
0004            COMMON/AAA/ M1                                                       000602
0005            COMMON/ELEVN/XKO,D,XL,ZO,Z1,EPS                                      000603
0006            EQUIVALENCE (FRIC(1),FRI1(1)),(FRIC(218),FRI2(1))                    000604
0007            DATA FRI1 / 1.,1.,17.,14.,1.E-06,1.E-05,5.E-05,1.E-04,2.E-04,        000605
               C4.E-04,6.E-04,8.E-04,1.E-03,2.E-03,4.E-03,6.E-03,8.E-03,1.E-02,      000606
               C1.5E-02,2.E-02,3.E-02,3.E+03,5.E+03,8.E+03,1.5E+04,3.E+04,6.E+04,    000607
               C1.E+05,2.E+05,4.E+05,8.E+05,2.E+06,4.E+06,8.E+06,1.E+07,.044,.037,   000608
               C.032,.0275,.023,.0198,.0178,.0155,.0138,.012,.0102,.0092,.0083,      000609
               C.0081,.044,.037,.032,.0275,.023,.0198,.0178,.0155,.0138,.0122,       000610
               C.0108,.0098,.0092,.0085,.044,.037,.032,.0275,.023,.0198,.018,.016,   000611
               C.0142,.013,.0118,.0112,.0109,.0108,.044,.037,.032,.0275,.023,        000612
               C.0202,.0184,.0164,.0145,.0137,.0128,.0122,.0120,.0120,.044,.037,     000613
               C.032,.0275,.024,.0208,.0190,.0170,.0158,.0149,.0141,.0139,.0138,     000614
               C.0138,.044,.037,.032,.0275,.0245,.0217,.020,.0182,.0172,.0167,       000615
               C.016,.016,.016,.016,.044,.037,.032,.0275,.025,.0222,.0208,.0192,     000616
               C.0183,.0180,.0175,.0175,.0175,.0175,.044,.0375,.033,.029,.0252,      000617
               C.023,.0215,.0202,.0195,.019,.0189,.0188,.0188,.0188,.044,.038,       000618
               C.034,.0295,.0258,.0235,.0222,.021,.0202,.02 ,.02,.02,.02,.02,.045,   000619
               C.039,.0355,.031,.028,.026,.025,.0242,.024,.0237,.0237,.0237,.0237,   000620
               C.0237,.047,.0415,.038,.034,.0315,.03,.0295,.029,.029,.029,.029,      000621
               C.029,.029,.029,.0485,.0435,.04,.0365,.0348,.0335,.033,.0325,.032,    000622
               C.032,.032,.032,.032,.032,.0495,.045,.042,.0395,.0375,.036,.0358,     000623
               C.0355,.0355,.0355,.0355,.0355,.0355,.0355 /                          000624
0008            DATA FRI2 / .052,.047,.044,.0415,.040,.039,.0382,.038,.038,.038,     000625
               C.038,.038,.038,.038,.055,.0515,.049,.0462,.045,.044,.044,.044,       000626
               C.044,.044,.044,.044,.044,.044,.059,.0555,.053,.051,.050,.049,.049,   000627
               C.049,.049,.049,.049,.049,.049,.049,.065,.063,.061,.059,.058,.0575,   000628
               C.0575,.0575,.0575,.0575,.0575,.0575,.0575,.0575 /                    000629
        C  FLOW IN PPH,DIA IN INCHES,ABS. VIS IN LBM/(FT*SEC),EPS IN INCHES          000630
0009            W=X9                                                                 000631
0010            A=PI*(D**2)/4.                                                       000632
0011            REY=(W*D/(A*VISC))*(12./3600.)                                       000633
0012            REY=ABS(REY)                                                         000634
0013            EOD=EPS/D                                                            000635
0014            CALL ENGUNB(FRIC,1,EOD,REY,FF,IE)                                    000636
0015            IF(REY.LT.3000) FF =64./(REY+.001)                                   000637
0016            Q=0.5*W*ABS(W)*144./(3600.)**2/RHO/(A**2)/32.2                       000638
0017            XK=XKO+FF*XL/D                                                       000639
0018            DP=XK*Q                                                              000640
0019            DP=DP+ RHO*(ZO-Z1)/1728.                                             000641
0020            F11=(X6-PAMB)-DP                                                     000642
0021            JJJ=MOD(M1,100)                                                      000643
0022            IF(JJJ.NE.0) GO TO 1000                                              000644
0023            WRITE(3,1100) REY,FF,Q,DP,F11                                        000645
0024       1100 FORMAT( 5E13.4)                                                      000646
0025       1000 CONTINUE                                                             000647
0026            RETURN                                                               000648
0027            END                                                                  000649
```